Atmospheric Test Models and Numerical Experiments for the Simulation of the Global Distributions of Weather Data Transponders

III. Horizontal Distributions

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Atmospheric Test Models and Numerical Experiments for the Simulation of the Global Distributions of Weather Data Transponders III. Horizontal Distributions

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ABSTRACT

A network of small balloon-borne transponders which gather very high resolution wind and temperature data for use by modern numerical weather predication models has been proposed to improve the reliability of long-range weather forecasts. The global distribution of an array of such transponders is simulated using LLNL's atmospheric parcel transport model (GRANTOUR) with winds supplied by two different general circulation models. An initial study used winds from CCM3 with a horizontal resolution of about 3 degrees in latitude and longitude, and a second study used winds from NOGAPS with a 0.75 degree horizontal resolution. Results from both simulations show that reasonable global coverage can be attained by releasing balloons from an appropriate set of launch sites.

I. INTRODUCTION

To improve the accuracy and range of weather forecasts, growth in the size and speed of computers has allowed numerical weather prediction models (NWP) to use increased spatial resolution. Concurrent with this increased resolution is a requirement for closely spaced measurements of atmospheric winds and temperatures. These data are necessary for model initialization, data assimilation, and validation of forecasts. Teller et al. (1998) proposed a high density global network of balloon-borne atmospheric micro transponders that would measure wind and temperature at a spatial density up to 3 km horizontally and 0.1 km vertically, i.e., $\sim 10^{11}$ balloons.

A crucial question pertinent to an array of free-floating balloons is whether a global distribution can be produced and maintained. This report addresses that question by describing numerical simulations in which balloons were released and tracked for several weeks. One set of simulations starts with a uniform global distribution of balloons and watches it change with time. The other releases balloons daily from a realistic but low density set of launch sites and examines the global distribution after several weeks. As we concluded in an earlier initial investigation (Grossman and Molenkamp, 1999a), reasonable global coverage of transponders can be achieved by launching balloons from a globally distributed set of launch sites.

II. MODELS AND PROCEDURES

The goal of this study is simply to determine the feasibility of establishing and maintaining a global array of balloon-borne micro transponders. The procedure is to specify a launch scenario, calculate balloon transport using the LLNL GRANTOUR model with winds from a general circulation model (GCM) and then assess the global coverage of the balloons with time. Since this is a feasibility study, a modest number of balloons ($\sim 10^5$) are tracked on ten standard pressure levels for 35 or 47 days depending on the GCM data available.

A. Transport Model - GRANTOUR

The LLNL GRANTOUR model (Walton, et al., 1988) was designed to study the transport, chemical interactions, and removal of atmospheric trace species. Among the trace species it has been used to simulate are tropospheric ozone (Penner *et al.*, 1991, 1994; Atherton *et al.*, 1995, 1996), atmospheric aerosols (Taylor and Penner, 1994; Chuang *et al.*, 1996), and dust (Rau *et al.*, 1994). GRANTOUR is a Lagrangian parcel model in which the atmosphere is treated as a set of constant-mass air parcels advected by wind fields input from a general circulation model. Many tests of the parcel transport component have validated its accuracy and make GRANTOUR an ideal model for simulating the movement of micro transponders in the atmosphere.

B. General Circulation Models

The Atmospheric Science Division at LLNL is currently using the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM3) (Kiehl et al., 1996) for application studies of climate change. We used CCM3 with T42/L18 resolution (64/128 latitude/longitude grid points, i.e. ~2.8°, and 18 vertical levels) to calculate global flow fields for 35 days from September 1 through October 5, 1990. The three dimensional winds and surface pressures, the necessary meteorological input for GRANTOUR balloon trajectory calculations, were saved at 4-hour intervals on the CCM3 grid. Grossman and Molenkamp (1999a) presented preliminary results using this meteorological data, but those simulations ignored vertical motion and did not include the loss of the balloons by surface collisions. The new results presented here include those effects.

A second set of meteorological data was provided by the Naval Research Laboratory's (NRL) NOGAPS (Navy Operational Global Atmospheric Prediction System) model (Hogan and Rosmond, 1991). NOGAPS is a numerical weather prediction model (NWP), while CCM3 is a climate model. NRL provided data from their archive, the resolution is T159/L42 (240/480 latitude/longitude grid points, i.e. 0.75°, and 24 vertical levels) and the time consisted of 47 days from August 15 through September 30, 1998 at 6-hour intervals.

The two sets of meteorological data cover different years so one cannot expect a direct correspondence between the balloon distributions. However, the data are for the same time of year (September) so seasonal differences should be small. Questions regarding seasonal variation should be addressed by simulation of a full annual cycle.

C. Vertical Levels

The global meteorological winds are read into GRANTOUR on the GCM's horizontal grid and hybrid vertical layers. GRANTOUR uses the same horizontal grid as the GCM, but it uses constant $\sigma = P/P_{sfc}$ levels in the vertical. Therefore, GRANTOUR must interpolate the winds from the global models' hybrid vertical layers to its constant σ levels. The σ's used by GRANTOUR are selected to correspond to the global models' hybrid levels at standard sea level pressure (1013.25 mb). Since terrain height is near sea level over most of the globe, the hybrid and σ levels are usually very close to each other.

In these simulations balloons are assumed to move along constant pressure surfaces except for a small displacement caused by the drag of vertical air motion. This is a simplifying assumption, because, without vertical drag, a balloon would move at a height determined by its density rather than its pressure. However, if the balloon's temperature remains equal to the surrounding atmosphere's temperature, the balloon would still move along a constant pressure surface since the density and pressure would change together. We used ten floating-level pressures in these simulations, 925, 850, 775, 700, 600, 500, 400, 300, 200, and 100 mb; each balloon is assigned one of these.

D. Vertical Motion

GRANTOUR provides a fully three-dimensional trajectory for its constant mass atmospheric parcels. Horizontal motion of micro transponders is the same as GRANTOUR's parcels, but the balloons do not move up and down with the vertical air velocity. In a companion report (Grossman and Molenkamp, 1999b) we consider the vertical motion of constant density atmospheric balloons and conclude that small micro transponder balloons would be tightly coupled to the reference density or pressure level with a displacement of less than 100 m for non-convective vertical velocities.

In this study we assumed balloon vertical motion is given by a simple restoring velocity equation,

$$\frac{d\sigma}{dt} = -k(\sigma - \sigma_e)$$

where σ is the vertical coordinate, k is a relaxation time coefficient, and σ_e, is the equilibrium vertical coordinate of the balloon. This equations simply forces the balloon to move to its equilibrium vertical coordinate exponentially with time. We further assume that

$$\sigma_e = \sigma_0 + \frac{\dot{\sigma}}{k}$$

where σ_0 is the specified floating-level pressure in σ coordinates and $\dot{\sigma}$ is the vertical air velocity. With an assumed value of 1 h^{-1} for k, balloons are occasionally found as far as 30 mb from their floating-level pressures. This is larger than the 100 m (10-20 mb) displacement indicated by the more complete analysis of vertical motion in Grossman and Molenkamp (1999b). In later plots of balloon locations, those more than 30 mb above their floating-level pressure are marked with a small plus symbol instead of a dot.

E. Terrain Effects

In our earlier report (Grossman and Molenkamp, 1999a) we ignored collisions of balloons with terrain. In this study we assume that a balloon hits terrain and is disabled when its calculated pressure is larger than the surface (terrain) pressure. Because terrain height is averaged over the area of each grid cell, terrain pressure depends very significantly on the resolution of the GCM. Since high mountains generally occupy small areas, mountains are taller (terrain pressures are smaller) for the higher resolution (smaller grid area) NOGAPS case than for CCM3. This can be clearly seen by comparing topography for the two models at the same pressure level in the later plots of balloon locations. Even the NOGAPS simulation has a tendency to underestimate the loss of balloons via terrain collisions because the roughness of topography permits many mountains to extend above the resolved terrain and it takes only one impact to destroy a balloon.

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F. Uniform Initial Distribution

The first scenario we considered was the deterioration of an initially uniform global distribution of balloons with time. At the beginning of the simulation 8192 balloons were placed at each of the ten floating-level pressures using the following procedure. First the globe was divided into 80 equal latitude bands. Next a number of balloons, N_b, equal to the fractional area of each band times 8192 was assigned to that band. Finally, at the central latitude of each band, N_b balloons were placed at longitude intervals of $360°/N_b$. The initial uniform distribution is shown in Figure 1. All the global plots in this report are equal area projections in which equal map areas represent equal global surface areas. This allows direct comparison of balloons densities at different locations on the map; however the shapes of continents and other map features are distorted.

G. Daily Release Scenario

The other scenario we examined was designed to simulate an operational global release of micro-transponder balloons, but for only a modest number of sites. Another constraint was to put a number of sites in each 10° latitude band proportional to its fractional area. Realizing that most of the globe is ocean, coastal areas were preferred for continental sites. Islands were used to disperse sites over the oceans and to provide global coverage. Still, significant oceanic areas have no islands and polar regions have no inhabitants, so we included seven aircraft routes to expand the global coverage of launch sites. From each launch site one balloon for each of the floating-level pressures was released at the beginning of each day during the simulation. Table 1 lists the
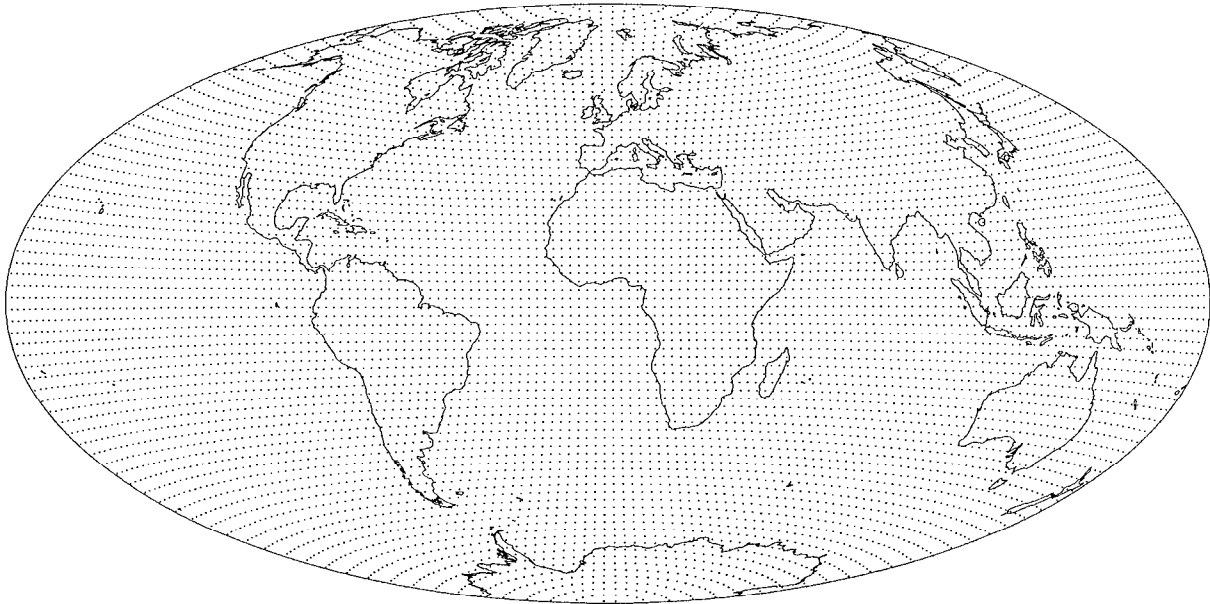
Figure 1. Initial balloon locations for the uniform global distribution. The base map is an equal area projection, i.e., equal map areas represent equal global surface areas; however continental shapes are distorted.

Table 1. Location of Launch Sites

Lat	Lon	Name	Lat	Lon	Name
80	20	Svalbard Islands	47	106	Ulan Bator, Mongolia
76	-69	Thule, Greenland	47	143	Sakhalin, Russia
74	-82	Dundas Harbor, Canada	46	-123	Portland, Oregon
74	111	Nordvik, Siberia	46	30	Odessa, Ukraine
73	-55	Upernavk, Greenland	45	126	Harbein, Mongolia
73	55	Novaya Zemlya, Siberia	43	-8	LaCaruna, Spain
71	-157	Barrow, Alaska	43	6	Marseille, France
71	-119	Fort Collinson, Canada	43	46	Groznyy, Georgia
70	-21	Scorbysand, Greenland	43	76	Alma-ata
69	20	Tromso, Norway	43	141	Sapporo, Japan
69	162	Ambarchik, Siberia	42	-88	Chicago, Illinois
68	72	Novyy Port, Siberia	42	-71	Boston, Mass.
66	-118	Great Bear Lake, Canada	41	-152	Airplane8-3
64	-166	Nome, Alaska	40	100	Tingshin, China
64	-51	Godthaab, Greenland	40	117	Peking, China
64	-21	Reykjavik, Iceland	39	-28	Azores
63	-68	Frobisher Bay, Canada	39	88	Charhlik, China
62	100	Tura, Russia	38	24	Athens, Greece
61	-135	Whitehorse, Canada	38	58	Ashkabad, Turkmenistan
60	5	Bergen, Norway	37	-121	Livermore, California
60	150	Magadan, Russia	37	-76	Norfolk, Virginia
60	169	Kavacha, Russia	37	3	Algiers, Algeria
59	-63	Ramah, Labrador	37	127	Seoul, Korea
59	30	St. Petersberg, Russia	36	-6	Gibralter, Spain
58	-94	Churchill, Canada	36	140	Tokyo, Japan
58	-3	Aberdeen, Scotland	35	-90	Memphis, Tennessee
57	-153	Kodiak, Alaska	35	33	Cyprus
55	61	Chelaybinsk, Russia	34	69	Kabul, Afghanistan
54	-113	Edmonton, Canada	33	-153	Airplanc8-2
54	124	Skovordino, Russia	33	-118	San Diego, California
53	-167	Unalaska, Alaska	33	13	Tripoli, Libya
53	-61	Goose Bay, Labrador	33	44	Baghdad, Iraq
53	22	Warsaw, Poland	32	-65	Bermuda
53	158	Petropavlosk, Kamchatka	31	121	Shanghai, China
50	-97	Winnipeg, Manitoba	30	31	Cairo, Egypt
50	-6	Land's End, UK	30	108	Chunking, China
50	80	Semipalatinsk, Russia	29	-119	Guadalupe Island
49	-150	Airplane8-4	29	-15	Canary Islands
48	-53	Saint John's, Newfoundland	28	-177	Midway Island
48	12	Munich, Germany	28	-99	Laredo, Texas

Table 1. (Cont.)

Lat	Lon	Name	Lat	Lon	Name
28	77	Delhi, India	12	53	Socotra Island
27	-155	Airplane8-1	12	72	Lacoadive Island, India
26	-80	Miami, Florida	12	93	Andamar Islands, India
26	128	Okinawa	11	106	Saigon, Vietnam
25	22	Buzaymah, Libya	10	-67	Caracas, Venezuela
25	47	Riyadh, Saudia Arabia	10	170	Marshall Islands
25	57	Trucial Coast	9	-130	Airplane1-2
24	10	Djanet, Algeria	9	-79	Panama City
24	67	Karachi, Pakistan	8	134	Palau Island
23	-110	Cabo San Lucas, Mexico	7	-162	Palmyra Islands
23	-65	Bahama	7	-58	Georgetown, British Guiana
23	80	Jabalpur, India	7	49	Garod, Somalia
22	-159	Lihue, Hawaii	7	80	Colombo, Ceylon
22	32	Wadi Halfa, Sudan	7	152	Truk Island
22	97	Mandalay, Burma	6	-11	Monrovia, Liberia
21	-87	Cancun, Mexico	6	-5	Abidjan, Ivory Coast
21	-17	Port Etienne	5	-74	Bogota, Columbia
21	106	Hanoi, Vietnam	5	-52	Cayenne, French Guiana
20	59	Oman	5	18	Bangui, Central African Rep.
20	145	Asuncion Island	5	32	Mongalla, Sudan
19	-156	South Point, Hawaii	5	95	Kutaradju, Sumatra
19	-111	Revilla Gigedo Island	5	115	Brunei
19	-99	Mexico City, Mexico	4	-124	Airplane1-3
19	73	Bombay, India	2	-156	Christmas Island
19	167	Wake Island	2	46	Mogadiscio, Madagascar
18	-65	Saint Thomas, Virgin Island	2	73	Maldive Island
17	-170	Johnson Island	1	-70	Mitu, Columbia
17	-25	Cape Verde Island	1	9	Libreville, Zaire
17	-3	Timbuktu, Mali	1	104	Diego-Suarez, Malagasy Rep.
15	-143	Airplane1-1	0	-174	Baker Island
15	-17	Dakar, Senegal	0	-78	Quito, Ecuador
15	64	Airplane9-5	0	170	Gilbert Islands
15	121	Manila, Phillipines	-1	-91	Galapagos Islands
14	33	Khartoum, Sudan	-1	80	Airplane9-4
14	145	Guam	-2	-117	Airplane1-4
13	-60	Barbados	-2	-50	Belem, Brazil
13	80	Madras, India	-2	30	Rwanda
12	-107	Clipperton Island	-2	138	Mataboor, West Irian
12	-87	Managua, Nicaragua	-4	-33	Fernando de Noronha Island
12	15	Fort Lamy, Chad	-4	15	Brazzaville, Congo

Table 1. (Cont.)

Lat	Lon	Name	Lat	Lon	Name
-4	55	Seychelles	-20	-41	Vitoria, Brazil
-4	122	Kendari, Celebes	-20	35	Beira, Mozambique
-6	72	Chagas Island	-20	58	Mauritius Island
-6	107	Djakarta, Indonesia	-20	119	Port Hedland, Australia
-6	155	Bougainville, Solomon Islands	-21	-175	Tonga, Island
-7	-173	Phoenix Island	-21	102	Airplane9-1
-7	-110	Airplane1-5	-22	15	Walvis Bay, S. Africa
-7	-80	Chiclago, Peru	-22	149	Mackay, Australia
-7	39	Dar es Salaam, Tanganyika	-22	166	Noumea, New Caledonia
-8	-149	Papeete, Tahiti	-23	-70	Antofagasta, Chile
-8	-35	Recife, Brazil	-23	-43	Rio de Janeiro, Brazil
-8	-14	Ascension Island	-23	134	Alice Springs, Australia
-8	86	Airplane9-3	-25	-136	Pitcairn Island
-9	13	Luanda, angola	-25	-125	Ducie Island
-9	25	Kamina, Congo	-25	-58	Asunsion, Paraguay
-10	-140	Marquesas Island	-25	45	Cape Saint Marie, Malagasy Rep.
-10	147	Port Moresby, New Guinea	-25	114	Carnarvon, Australia
-10	160	Guadalcanal	-26	-80	San Felix Island
-11	-69	Mogadiscio, Somalia	-26	-30	Airplane3-1
-11	-49	Porto Nacional, Brazil	-26	28	Pretoria, S. Africa
-12	-103	Airplane1-6	-27	-110	Easter Island
-12	-77	Lima, Peru	-27	170	Norfolk Island
-12	49	Diego-Suarez, Malagasy Rep.	-28	153	Brisbane, Australia
-12	96	Cocas Island	-29	17	Alexander Bay
-12	131	Darwin, Australia	-30	-177	Raoul I., Kermadec I.
-13	-38	Salvador, Brazil	-30	-51	Porto Alegre, Brazil
-14	-172	Apia, Samoa	-30	32	Durban, S. Africa
-15	12	Mocamedes, Angola	-31	-64	Cordoba, Argentina
-15	168	Espiritu Santo, New Hebrides	-31	-30	Airplane3-2
-16	-56	Cuiaba, Brazil	-31	134	Tarcoola, Australia
-16	-7	St Helena Island	-32	116	Perth, Australia
-16	40	Antonio Enes, Mozambique	-33	-71	Santiago, Chile
-16	127	Derby, Australia	-34	-87	Juan Fernando Island
-17	-140	Tuamotu Island	-34	18	Capetown, S. Africa
-17	-97	Airplane1-7	-34	151	Sydney, Australia
-17	96	Airplane9-2	-35	-57	Montevideo, Uruguay
-17	146	Cairns, Australia	-35	173	North Cape, NZ
-18	-70	Tacna, Peru	-36	-30	Airplane3-3
-18	26	Victoria Falls, S. Rhodesia	-37	-12	Tristan da Cuhna Island
-18	178	Sava, Fiji	-37	116	Airplane2-1

Table 1. (Cont.)

Lat	Lon	Name	Lat	Lon	Name
-37	175	Auckland, NZ	-52	168	Airplane4-D
-38	-62	Bahia Blanca, Argentina	-53	-71	Punta Arenas, Chile
-38	20	Airplane4-1	-53	-57	Palmer Station
-38	78	Amsterdam Island	-54	-37	South Georgia Island
-38	145	Melbourne, Australia	-55	159	Macquarie Island
-40	-71	Valdivia, Chile	-57	-110	Airplane6-9
-40	-11	Gough Island	-57	28	Airplane4-5
-41	-30	Airplane3-4	-57	70	Airplane6-2
-41	175	Wellington, NZ	-57	119	Airplane2-5
-42	-110	Airplane6-C	-58	-80	Airplane2-9
-42	116	Airplane2-2	-62	-110	Airplane6-8
-42	147	Hobart, Tasmania	-62	-60	South Shetland Islands
-43	22	Airplane4-2	-62	33	Airplane4-6
-44	-176	Chatham Island	-62	70	Airplane6-3
-44	173	Christchurch, NZ	-62	160	Airplane4-C
-46	-67	Comodoro Rivadavia, Argentin	-64	120	Airplane2-6
-46	-30	Airplane3-5	-67	-110	Airplane6-7
-47	-110	Airplane6-B	-67	39	Airplane4-7
-47	38	Prince Edward Island	-67	70	Airplane6-4
-47	51	Crozet Island	-67	155	Airplane4-B
-47	117	Airplane2-3	-68	-80	Airplane2-8
-47	168	Half-moon Bay, NZ	-71	145	Airplane4-A
-48	24	Airplane4-3	-72	-110	Airplane6-6
-49	69	Kerguelen Island	-72	50	Airplane4-8
-52	-110	Airplane6-A	-77	-160	Little America
-52	-60	Falkland Island	-77	165	McMurdo Sound
-52	25	Airplane4-4	-78	100	Airplane4-9
-52	70	Airplane6-1	-79	-75	Airplane2-7
-52	118	Airplane2-4	-88	70	Airplane6-5

Table 2. Daily Aircraft Flights

Flight	Route	Sites
1	Honolulu-Santiago, Chile	7
2	Punta Arenas, Chile-Perth, Australia	9
3	Rio de Janeiro (South Atlantic)	5
4	Capetown-Christchurch, NZ	13
6	Easter Island-Kerguelen Island	12
8	Honolulu-Anchorage	4
9	Bombay, India-Perth, Australia	5

298 ground and aircraft launch sites; Table 2 identifies each aircraft route and its corresponding number of launch sites. The release sites are shown in Figure 2. Beyond the simple assumptions given above, no attempt was made to optimize the daily release scenario.
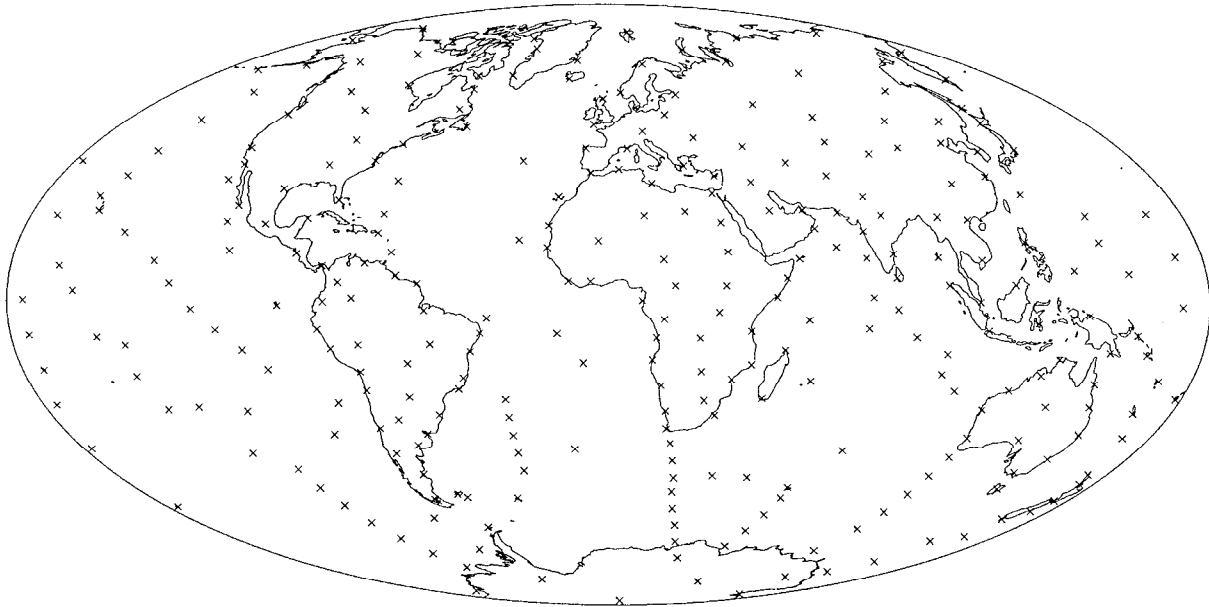
Figure 2. Daily release sites.

III. SIMULATION STUDIES

A. Uniform Initial Distribution

1. CCM3/GRANTOUR

The CCM3/GRANTOUR simulation of the uniform initial distribution runs for 35 days. Balloon locations at the end of this period are shown in Figures 3-12 for each of the ten vertical levels from lowest (925 mb) to highest (100 mb). Balloons are represented by dots in these equal area projections.

The number of balloons allocated to each floating-layer pressure is 8192, but some balloons with large floating-layer pressures would be below terrain and are not released. In addition balloons with large floating-layer pressures are lost due to collisions with terrain. Table 3 gives the number of balloons initially released at each pressure after deducting those below terrain and it gives the number of balloons still aloft at the end of 35 days. Since no terrain penetrates above 500 mb all 8192 balloons allocated to these layers are released and remain aloft for 35 days.

Inspection of the plots in Figures 3-12 indicates that the uniform distribution deteriorates in all layers, but it deteriorates more rapidly in some layers than in others. Layers near the surface develop areas with very sparse coverage quite rapidly. This decay is due to loss of balloons by collisions with terrain and to horizontal divergence and convergence in the large scale flow. At mid-latitudes in both the southern and northern hemispheres, the predominant zonal flow transports balloons west to east around the globe with high terrain areas removing balloons as they pass. Consequently, massive areas downwind of the mountains such as the eastern United

Table 3. Number of Balloons Released and Aloft after 35 Days

Levels (mb)	CCM3/GRANTOUR			NOGAPS/GRANTOUR		
	Allocated	Released	Aloft	Allocated	Released	Aloft
100-500	8192	8192	8192	8192	8192	8192
600	8192	8168	7906	8192	8157	7779
700	8192	8070	7694	8192	8030	6971
775	8192	7995	7164	8192	7933	6181
850	8192	7862	6080	8192	7739	4395
925	8192	7378	3390	8192	7257	2168

States, South America, and Asia have almost no balloons. In mid-latitudes balloons tend to gather in clusters or ribbons along convergence lines, presumably in frontal zones, since the clusters and ribbons move from day to day. One shortcoming of these simulations is a lack of any diffusive component to the flow field; i.e., the balloons are transported solely with the large-scale winds. Therefore, once balloons converge they have no way of moving away from each other, and the simulation over-estimates balloon clustering.

In the tropics, vast areas are almost completely without balloons while several small areas have collected many balloons. These convergence areas include the Carribean Sea, northern Arabian Sea, central India, and the South China Sea. The equatorial zone is nearly free of balloons while a surplus exists in the inter-tropical convergence zone. This is consistent with divergence in the central tropics and convergence just to the north and south.

The north-polar region has quite good coverage after 35 days except at the lowest level (925 mb) where the mountains in Greenland and northern Canada/Alaska have removed many balloons. Terrain near the south pole is all above 700 mb so no low elevation balloons are found there.

Balloons with floating-level pressures in the middle of the atmosphere (between 775 and 400 mb) maintain good global distributions, although the spacings do not stay very uniform. The distributions are particularly good in mid-latitudes and in polar regions. Nevertheless, coverage problems still exist in the tropics, especially for balloons assigned to 775 and 700 mb.

The global distribution of balloons with floating-level pressures near the tropopause (300 and 200 mb) is poor after 35 days. The tropics are almost completely devoid of balloons probably due to upper level divergence associated with the Hadley circulation. The balloons advected out of the tropics are found primarily along meandering lines at the edge of the tropics, particularly for balloons with floating-level pressures of 200 mb. The mid-latitudes and polar regions have very good coverage with the number of balloons enhanced by transport from the tropics.

Balloons with floating-level pressures of 100 mb preserve very good global coverage; however, the reliability of the simulation at this level is subject to uncertainty because GCM's, designed to simulated the troposphere, may not accurately calculate flow fields in the stratosphere.

2. NOGAPS/GRANTOUR

The NOGAPS/GRANTOUR uniform distribution simulation was run for 47 days from August 15 to September 30, 1998. Balloon locations at each pressure level after 35 days are shown in Figures 13-22 for comparison with the CCM3/GRANTOUR simulation and after 47 days in Figures 23-32. Comparison of terrain represented by the gray shaded areas in Figures 3-7 with Figures 13-17 at corresponding pressure levels reveals the higher spatial resolution of the NOGAPS topography and the greater extent of areas of high mountains. For example, the Andes

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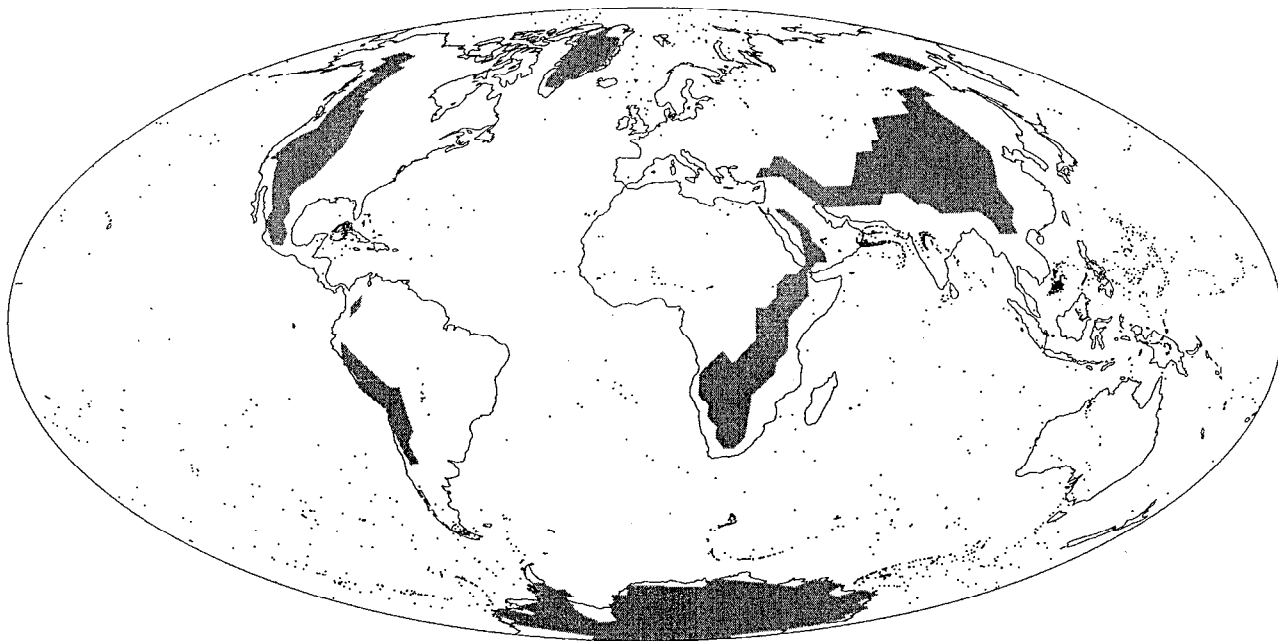
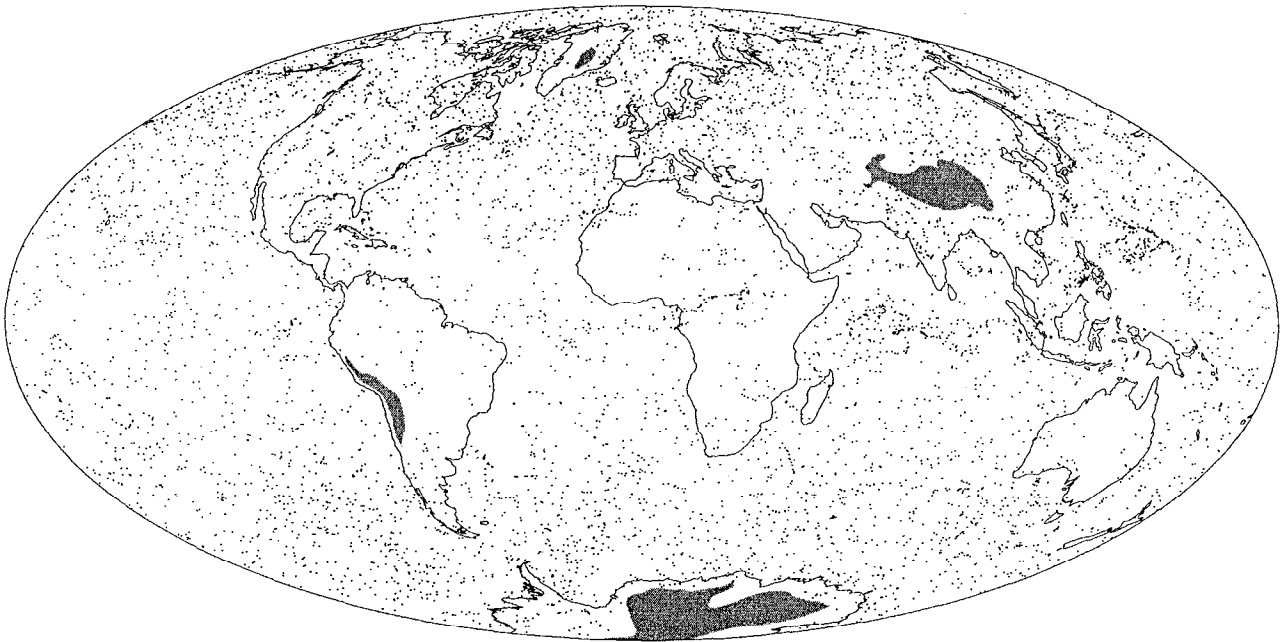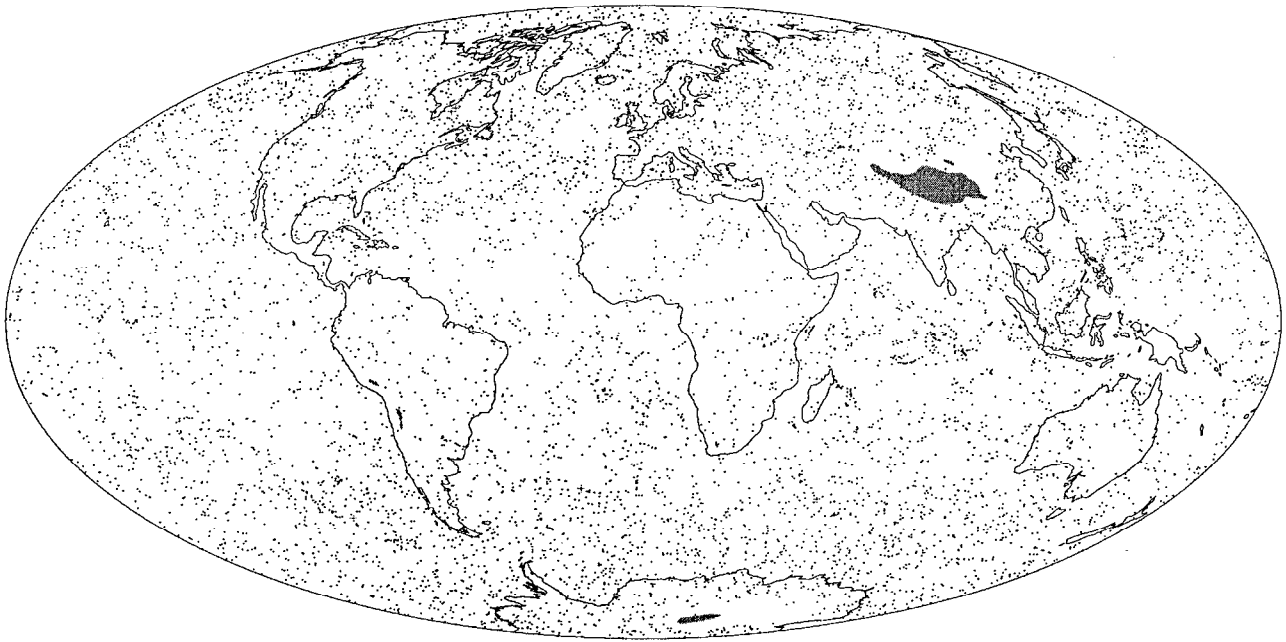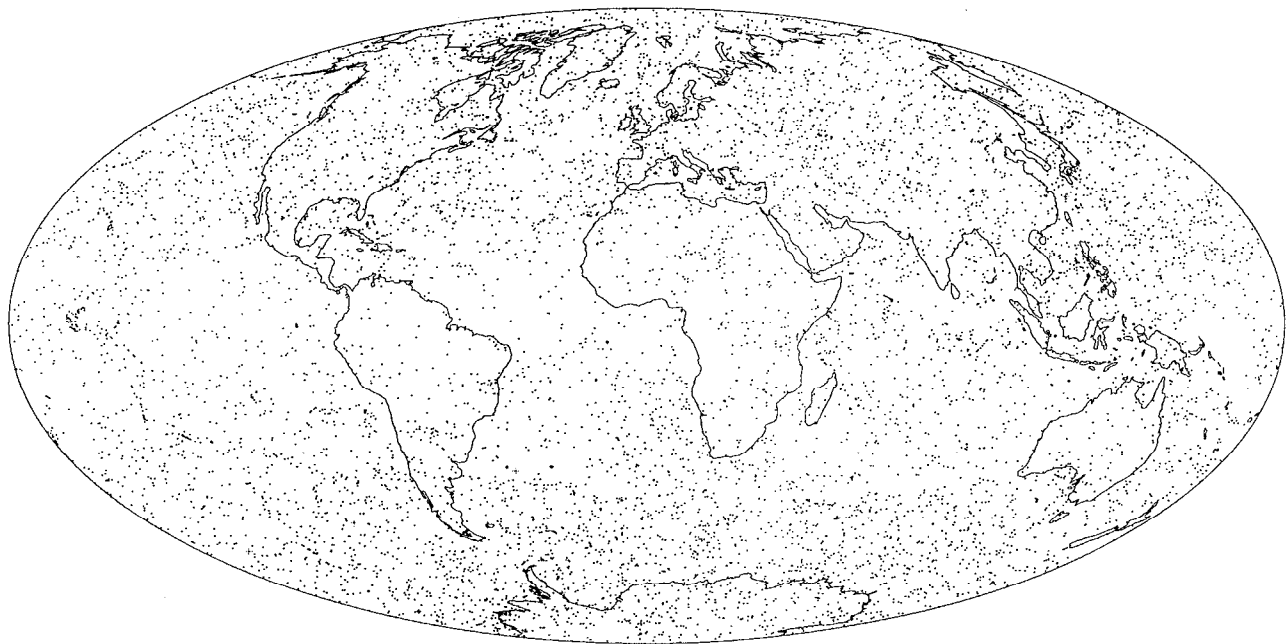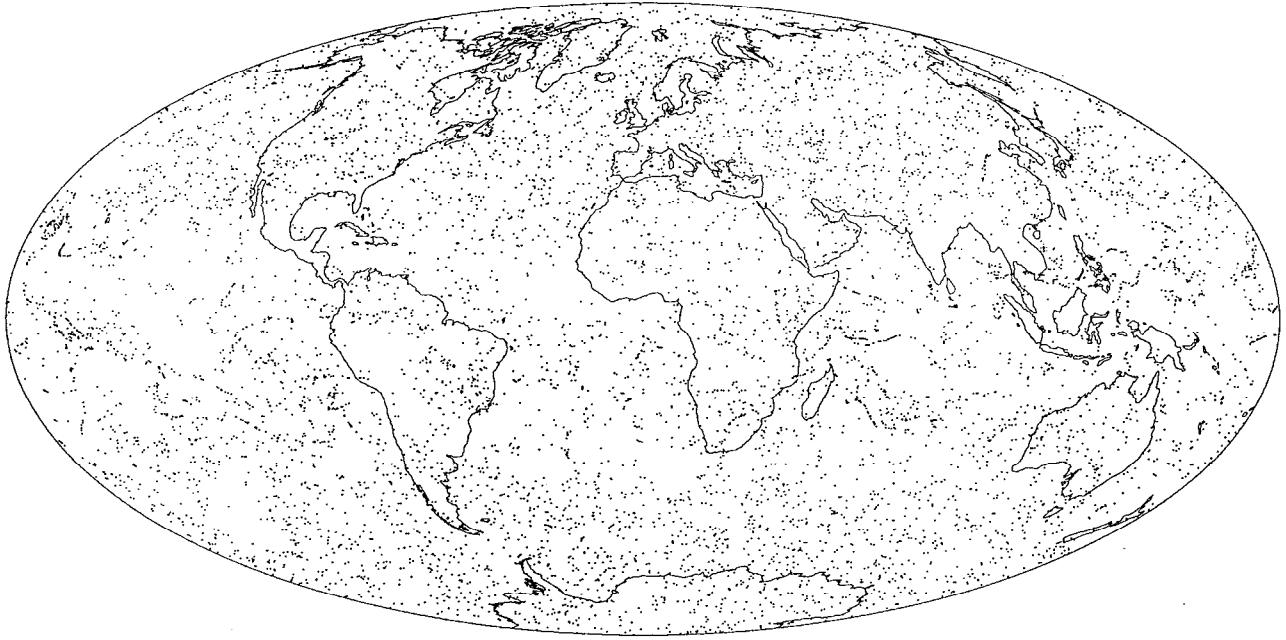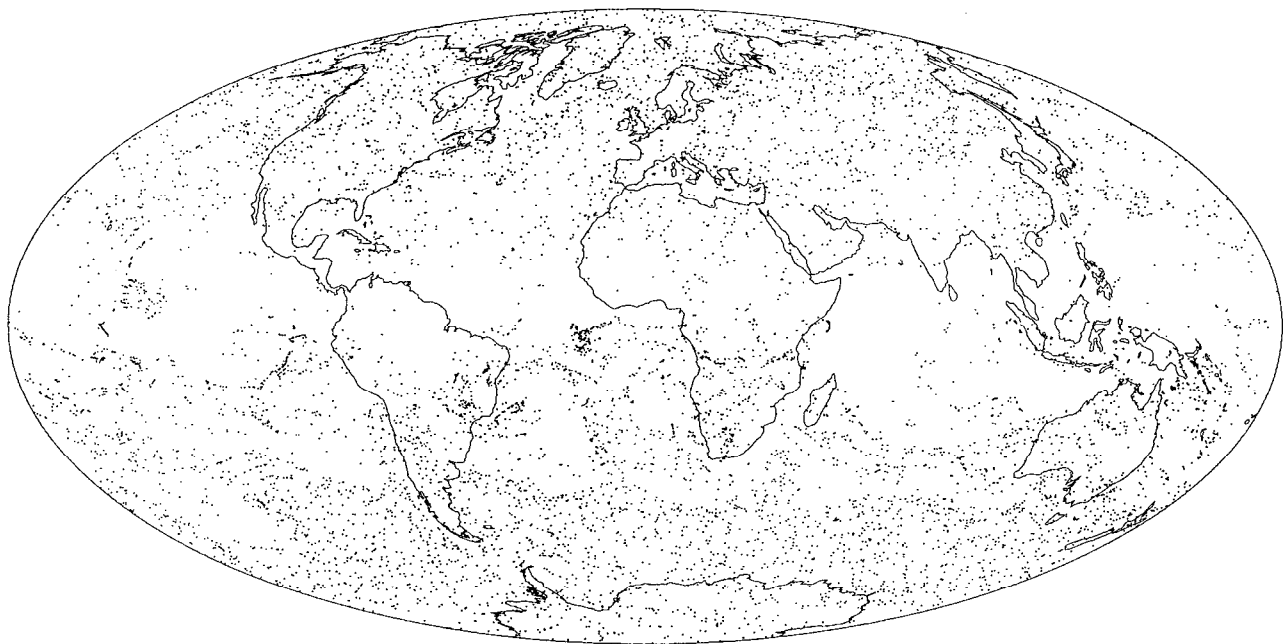**Figure 3**. Location of balloons set for 925 mb 35 days after release as an initially uniform distribution. Terrain above 925 mb is shaded in gray. 7387 balloons released, 3390 still aloft, 3997 hit terrain.
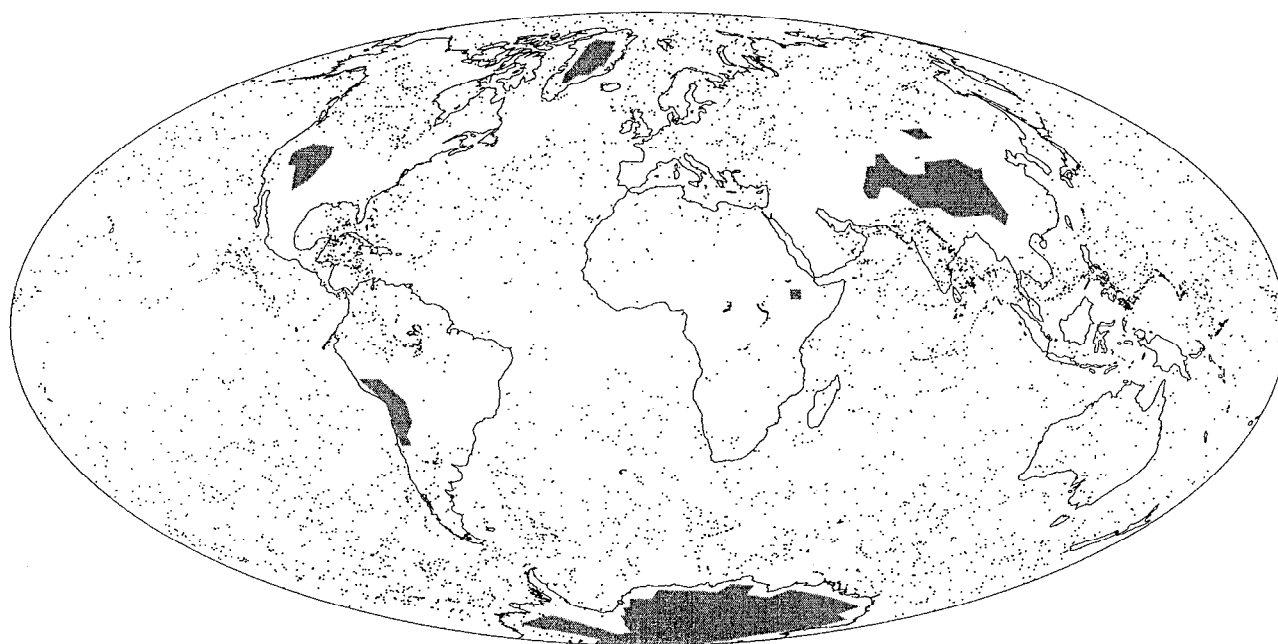
Figure 4. Location of balloons set for 850 mb 35 days after release as an initially uniform distribution. Terrain above 850 mb is shaded in gray. 7862 balloons released, 6080 still aloft, 1782 hit terrain.
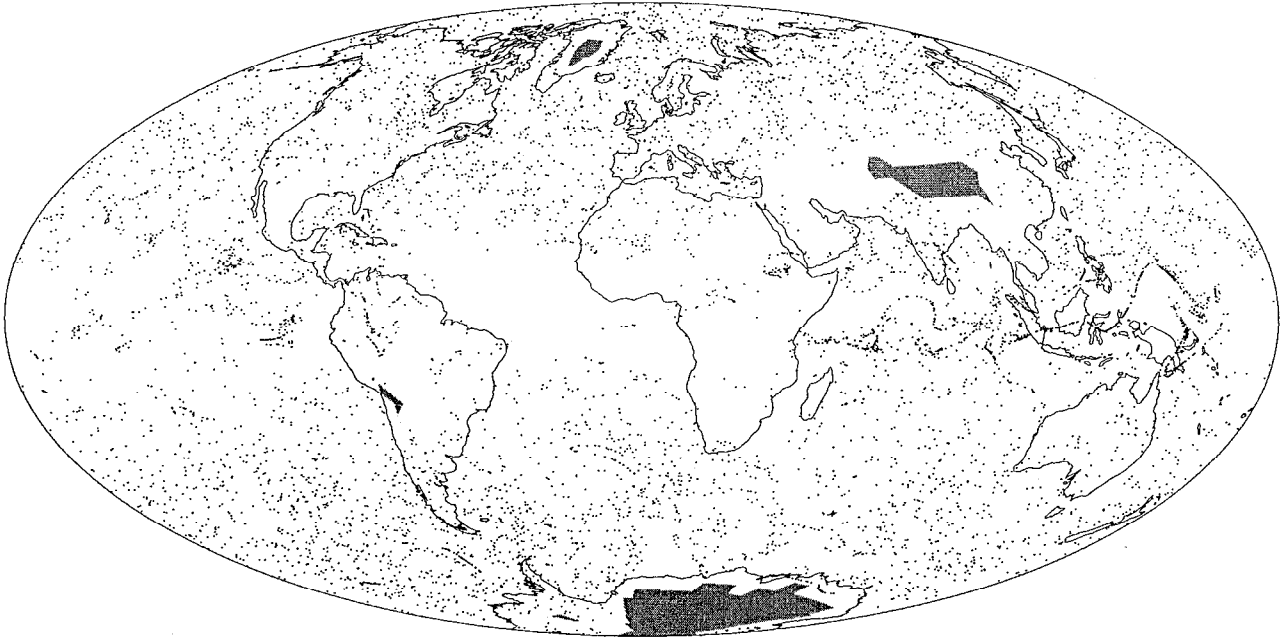
Figure 5. Location of balloons set for 775 mb 35 days after release as an initially uniform distribution. Terrain above 775 mb is shaded in gray. 7995 balloons released, 7164 still aloft, 831 hit terrain.
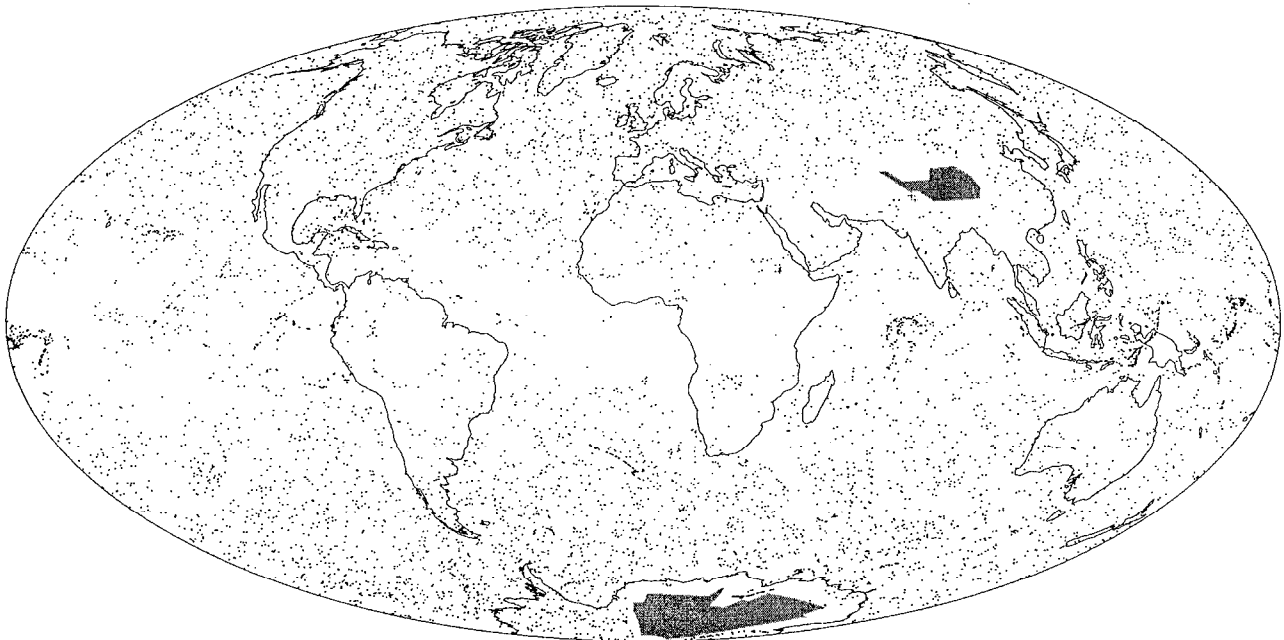
Figure 6. Location of balloons set for 700 mb 35 days after release as an initially uniform distribution. Terrain above 700 mb is shaded in gray. 8070 balloons released, 7897 still aloft, 376 hit terrain.
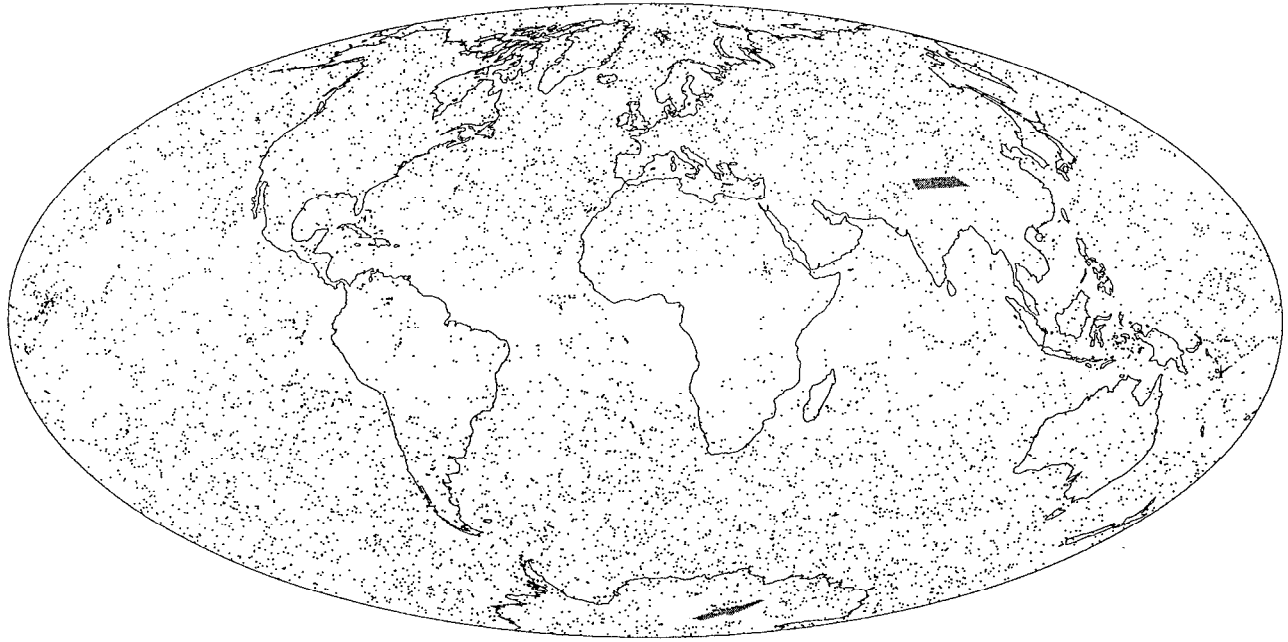
Figure 7. Location of balloons set for 600 mb 35 days after release as an initially uniform distribution. Terrain above 600 mb is shaded in gray. 8168 balloons released, 7906 still aloft, 262 hit terrain.
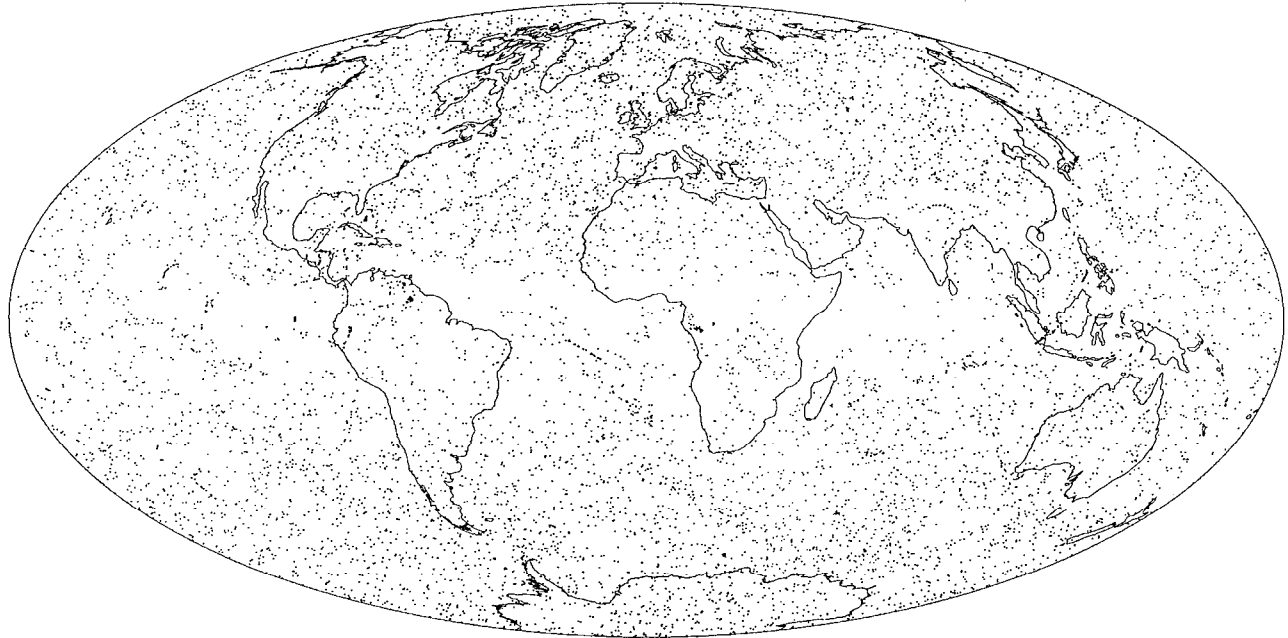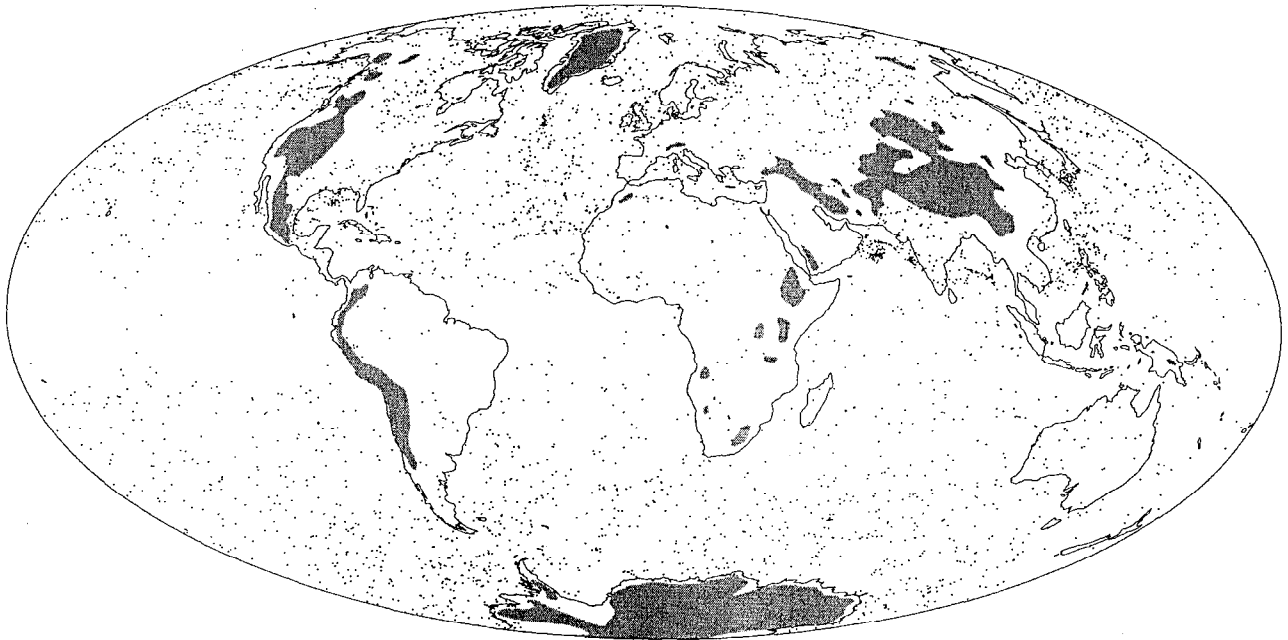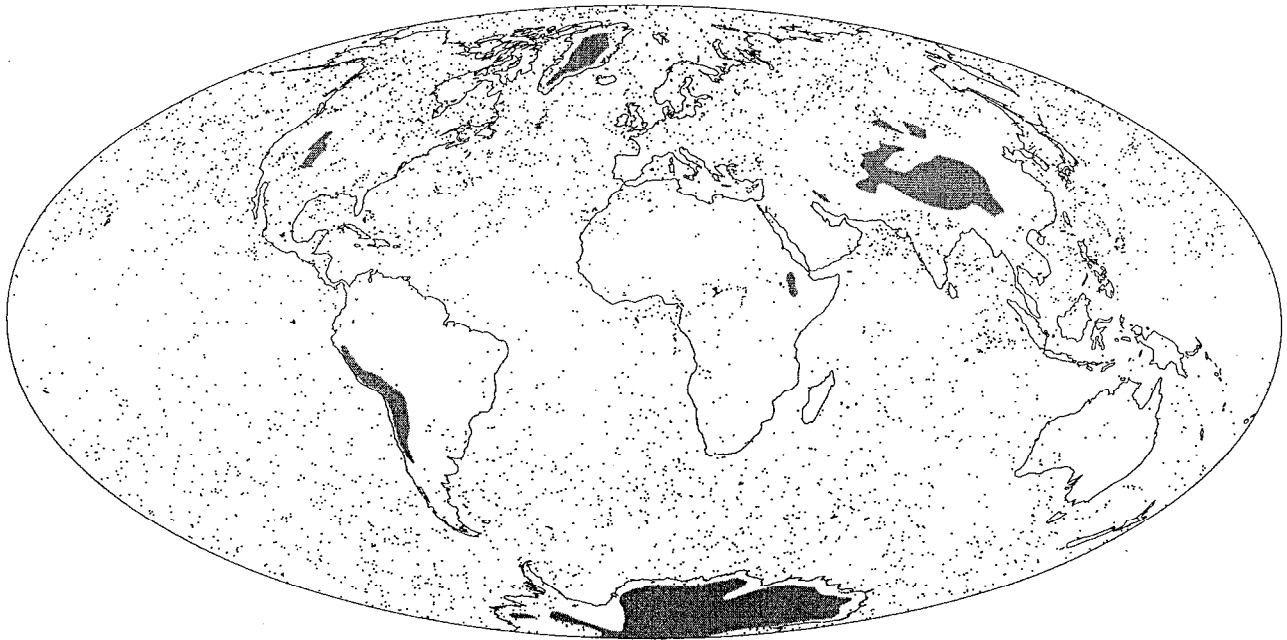

Figure 8. Location of balloons set for 500 mb 35 days after release as an initially uniform distribution. 8192 balloons released and still aloft.
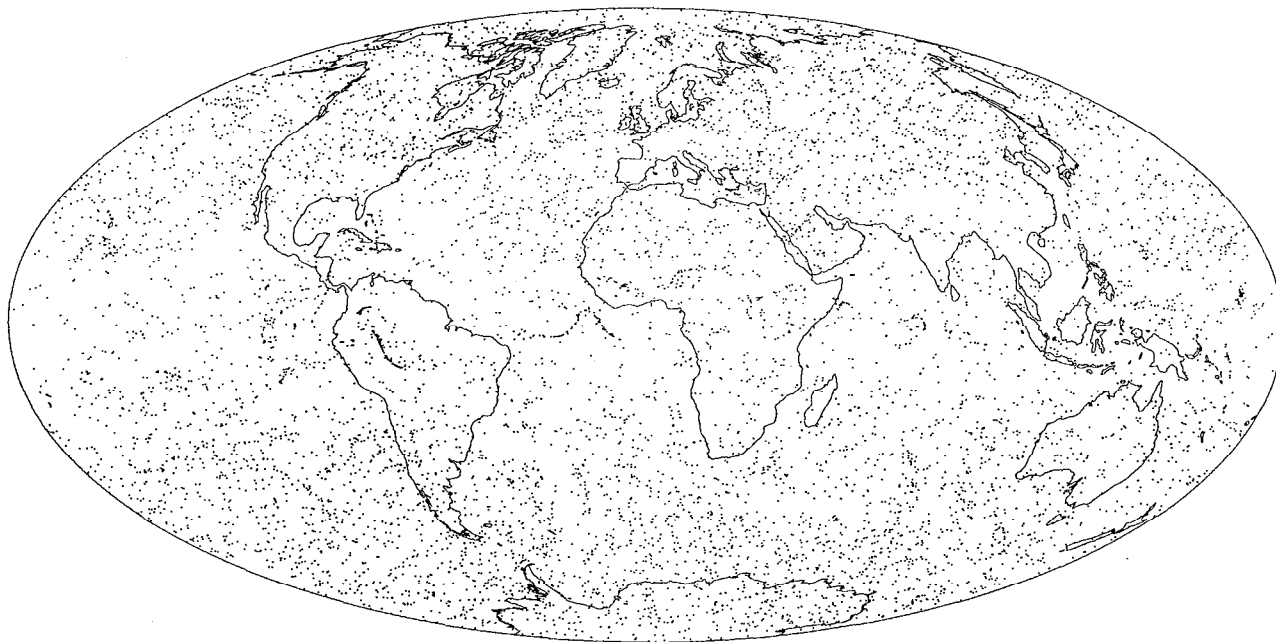
Figure 9. Location of balloons set for 400 mb 35 days after release as an initially uniform distribution. 8192 balloons released and still aloft.
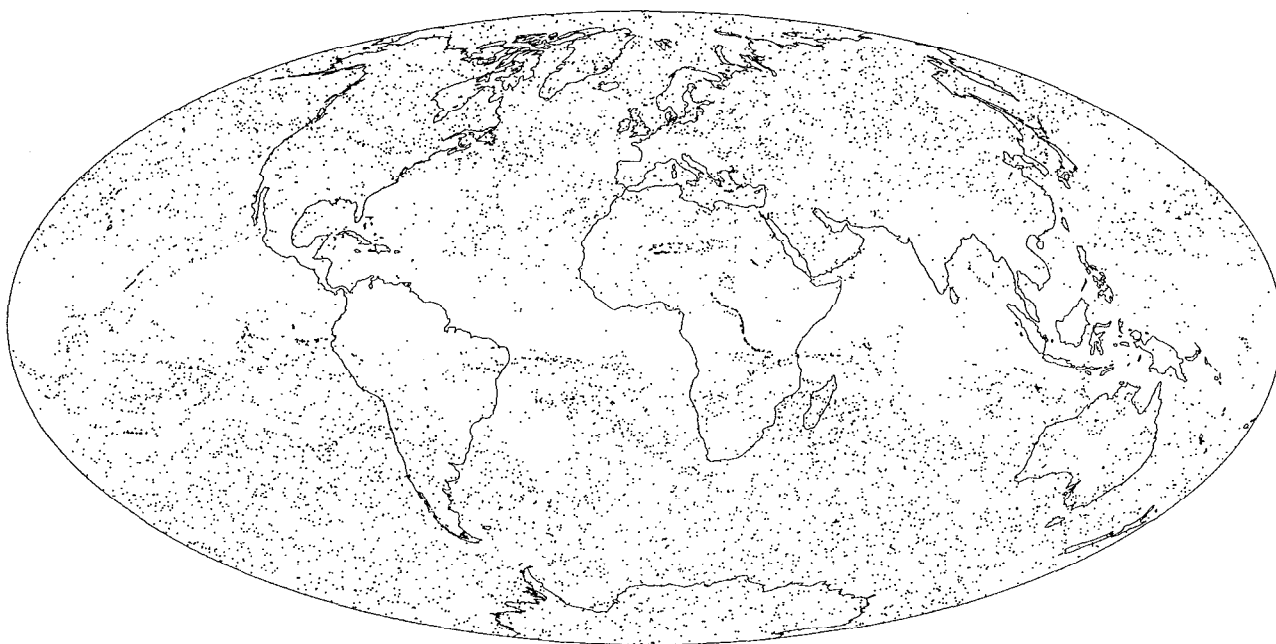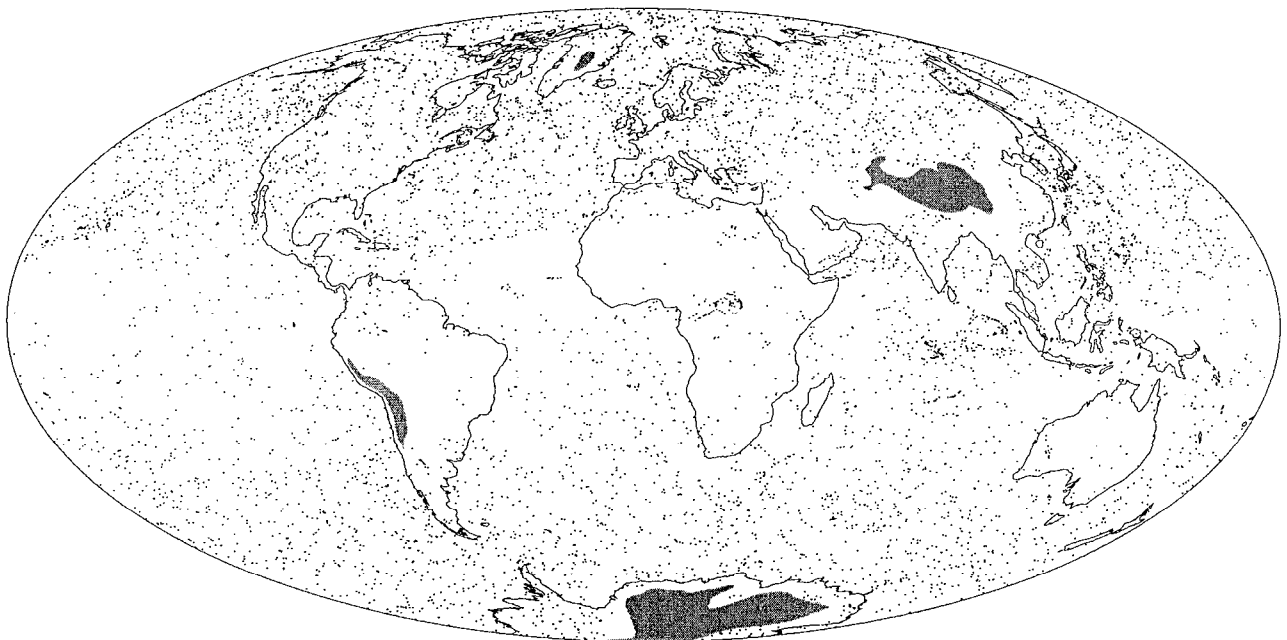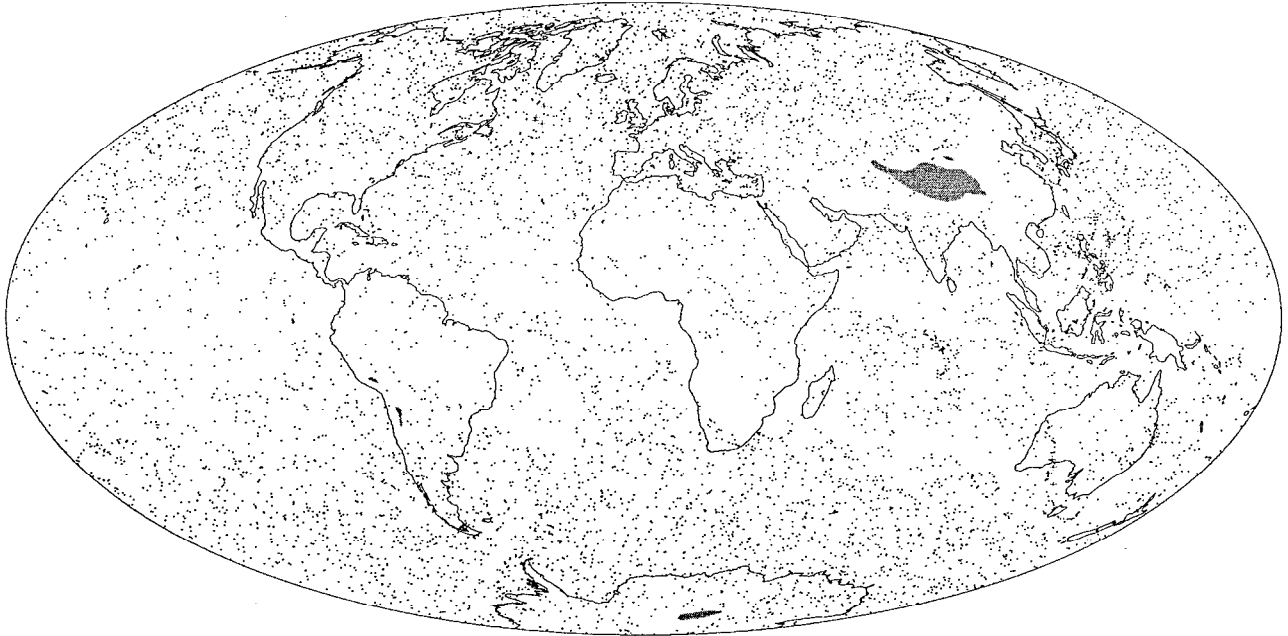

Figure 10. Location of balloons set for 300 mb 35 days after release as an initially uniform distribution. 8192 balloons released and still aloft.
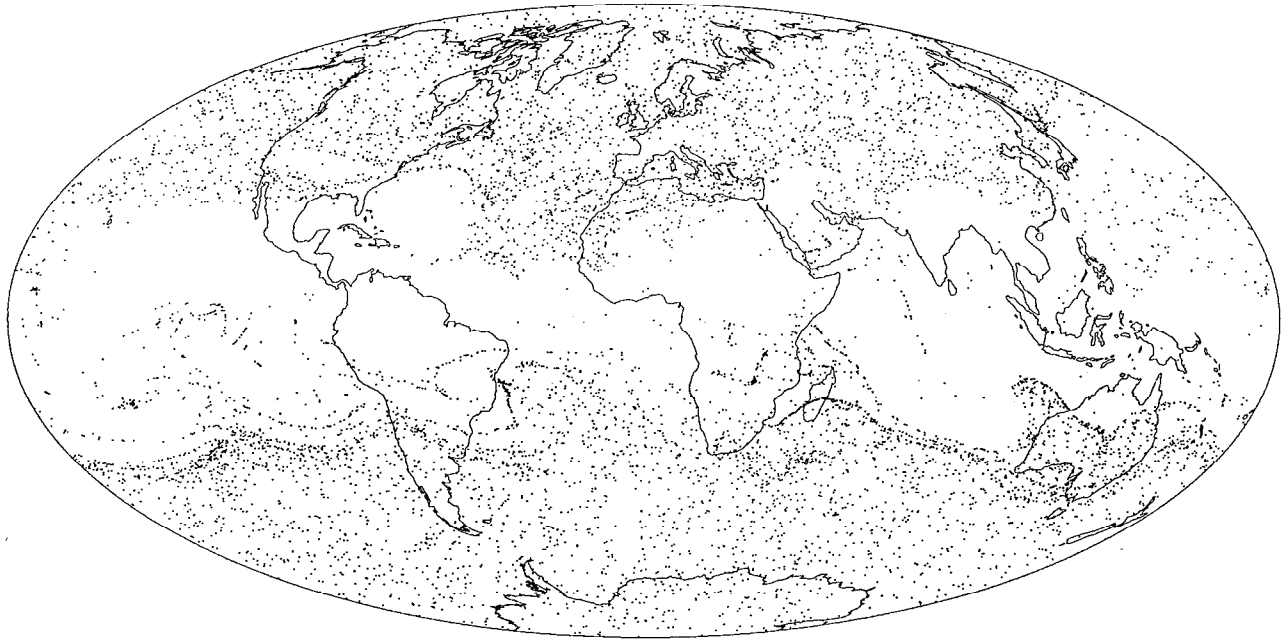
Figure 11. Location of balloons set for 200 mb 35 days after release as an initially uniform distribution. 8192 balloons released and still aloft.
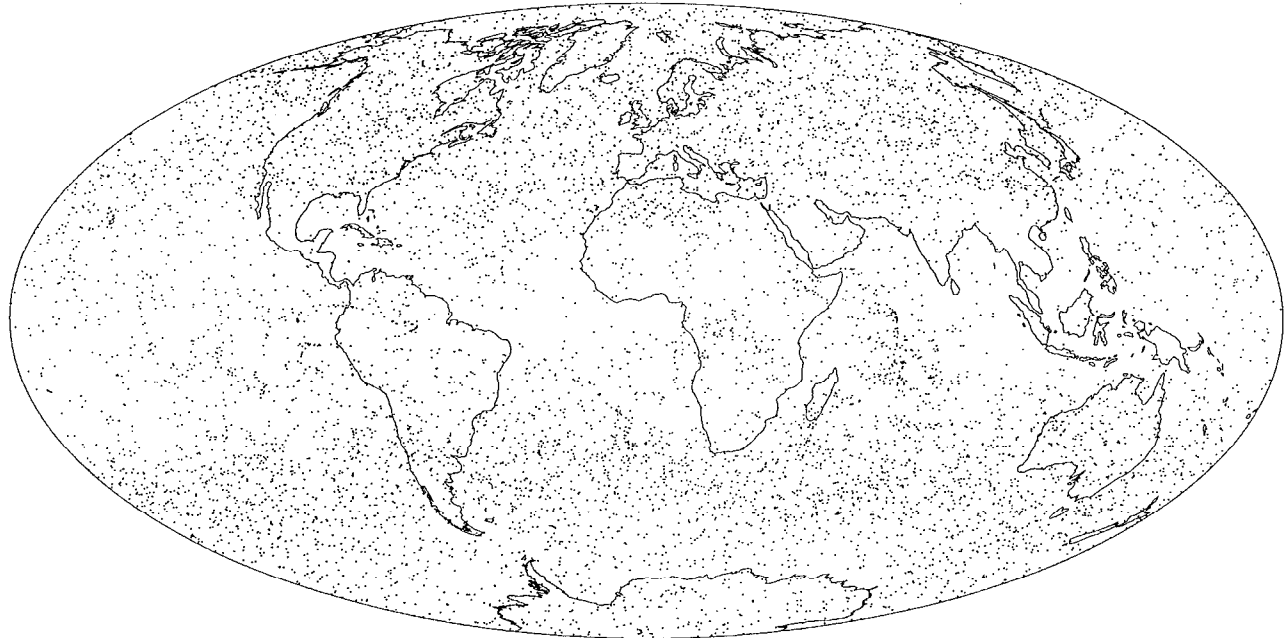
Figure 12. Location of balloons set for 100 mb 35 days after release as an initially uniform distribution. 8192 balloons released and still aloft.
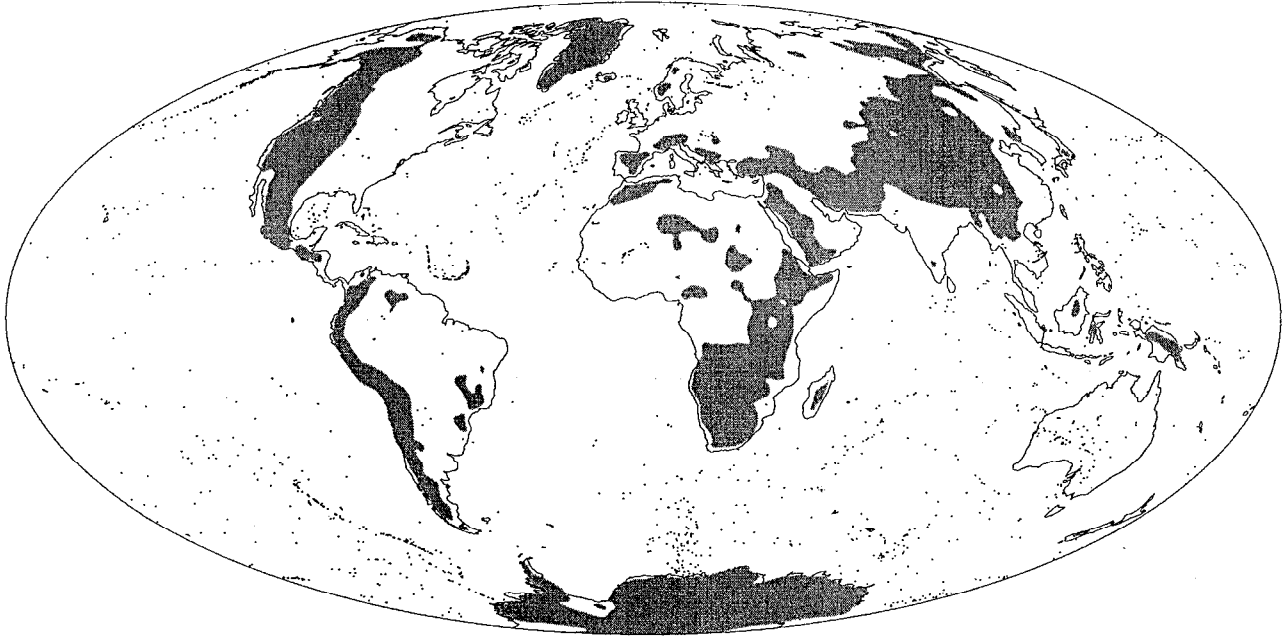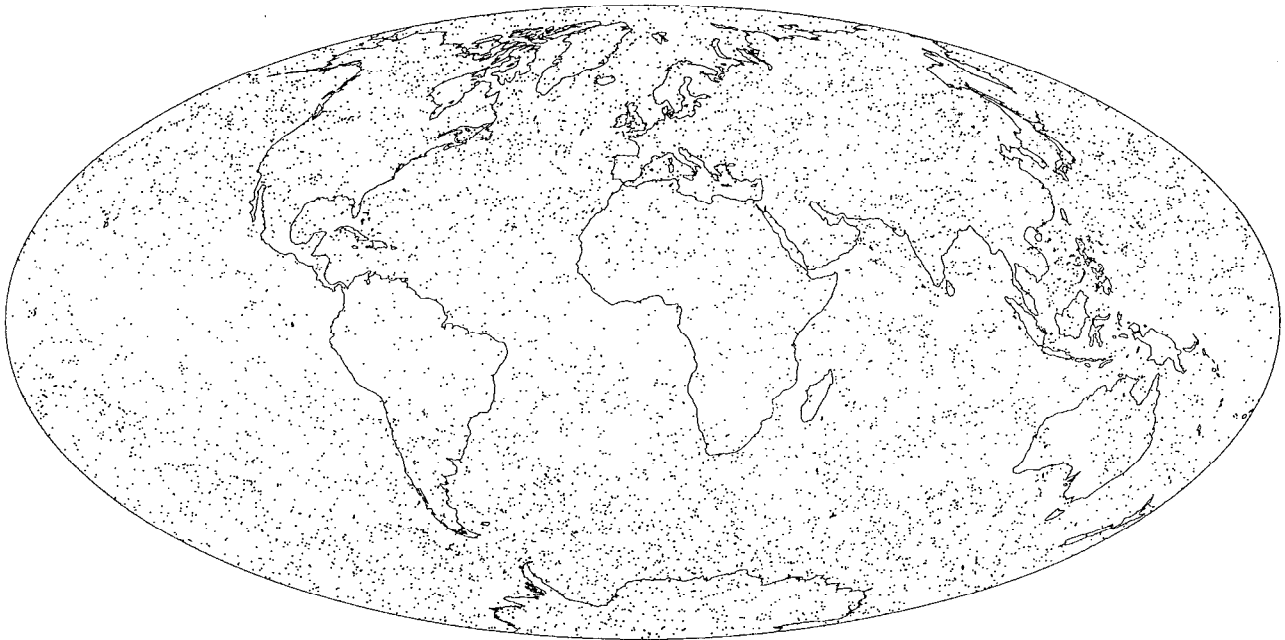
Figure 13. Location of balloons set for 925 mb 35 days after release as an initially uniform distribution. Terrain above 925 mb is shaded in gray. 7257 balloons released, 2168 still aloft, 5089 hit terrain.
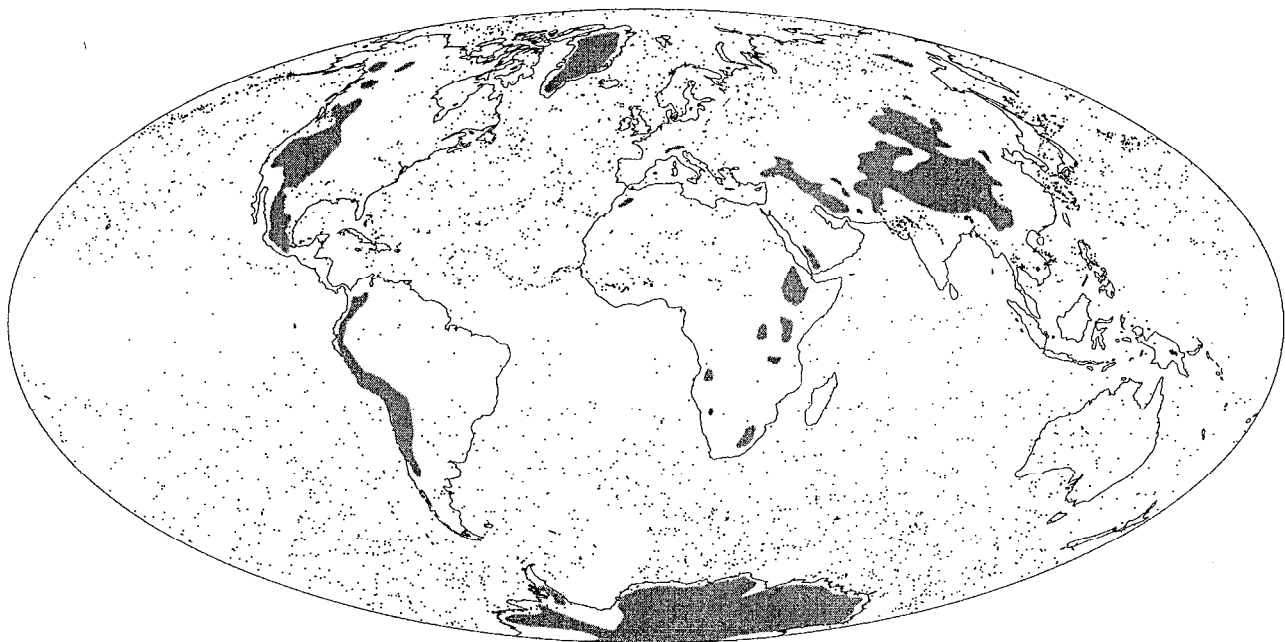
Figure 14. Location of balloons set for 850 mb 35 days after release as an initially uniform distribution. Terrain above 850 mb is shaded in gray. 7739 balloons released, 4395 still aloft, 3344 hit terrain.

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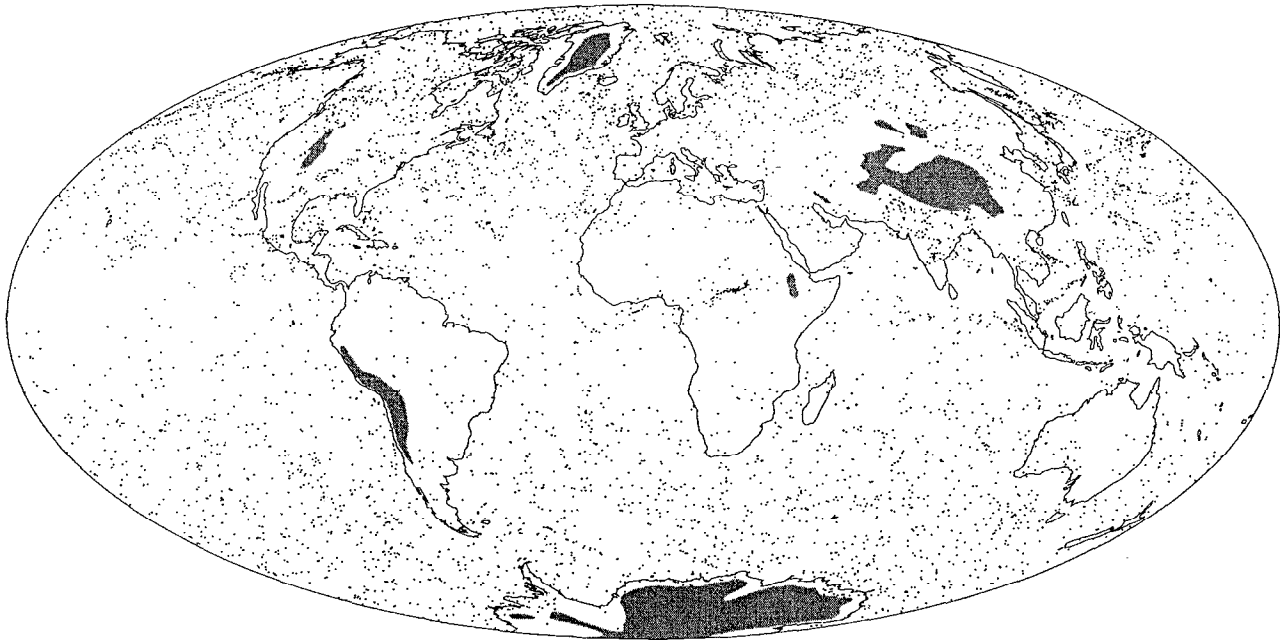
Figure 15. Location of balloons set for 775 mb 35 days after release as an initially uniform distribution. Terrain above 775 mb is shaded in gray. 7933 balloons released, 6181 still aloft, 1752 hit terrain.
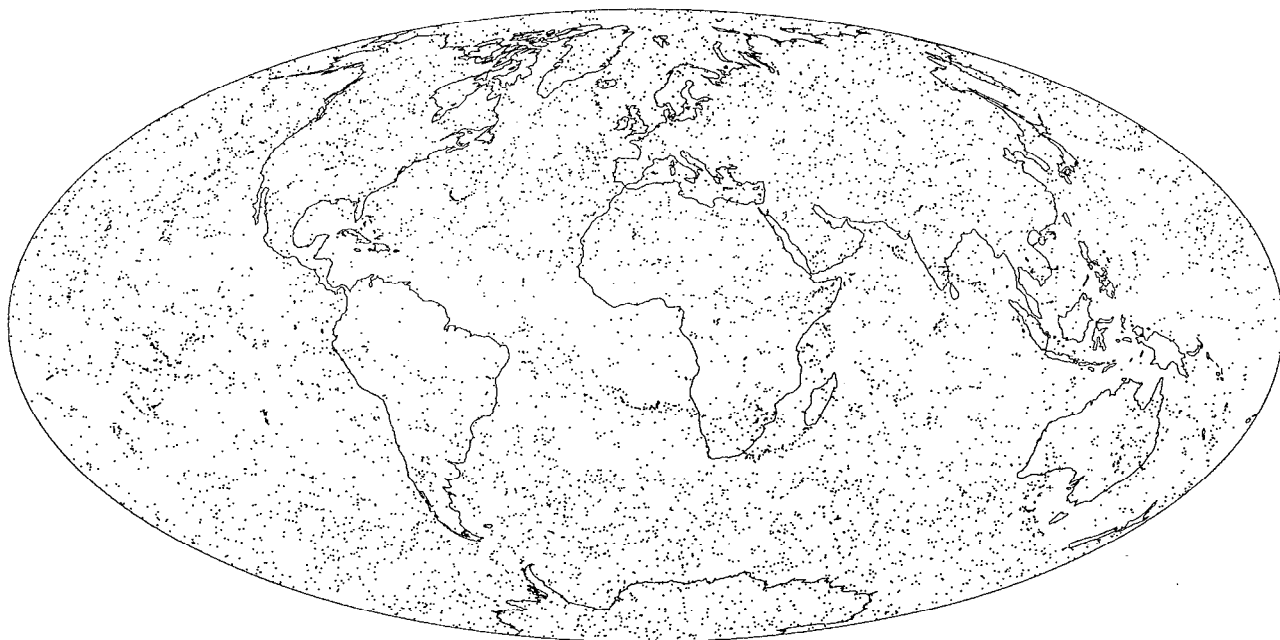

Figure 16. Location of balloons set for 700 mb 35 days after release as an initially uniform distribution. Terrain above 700 mb is shaded in gray. 8030 balloons released, 6971 still aloft, 1059 hit terrain.
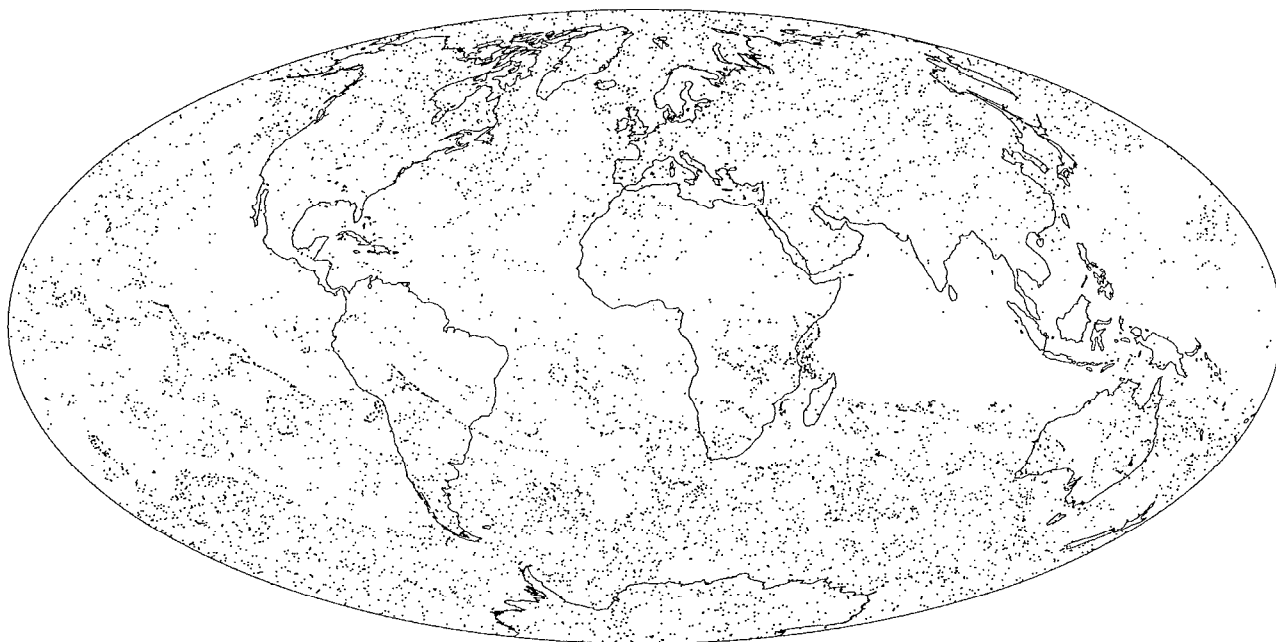
Figure 17. Location of balloons set for 600 mb 35 days after release as an initially uniform distribution. Terrain above 600 mb is shaded in gray. 8157 balloons released, 7779 still aloft, 378 hit terrain.
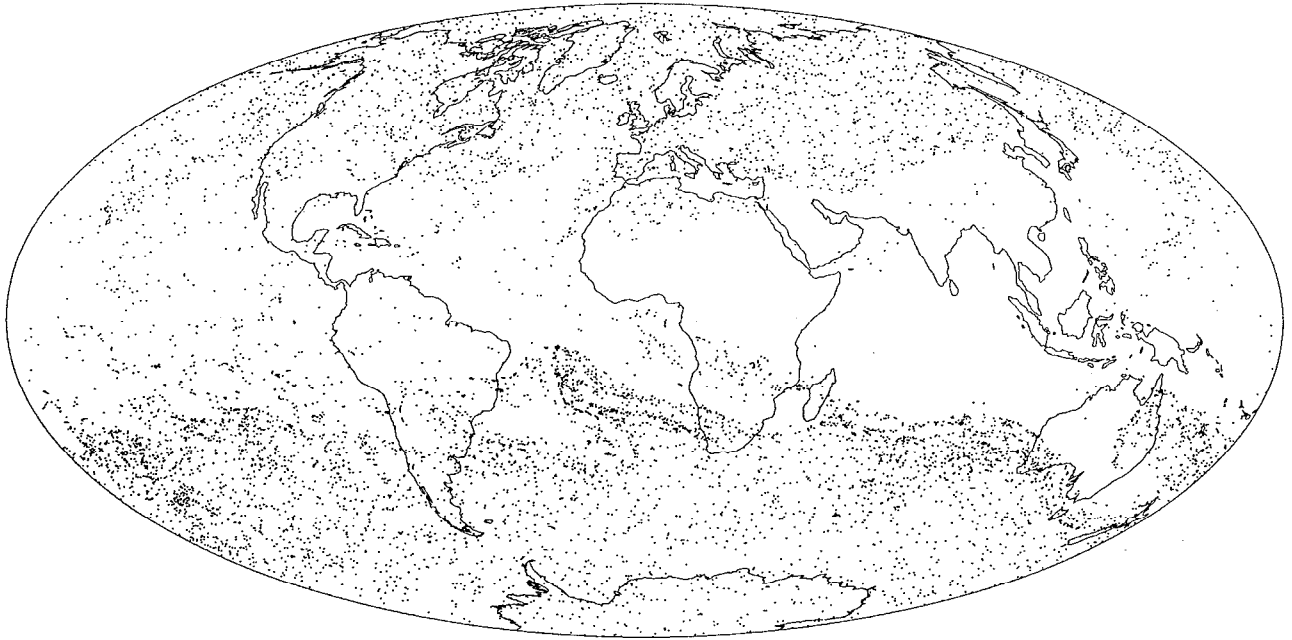

Figure 18. Location of balloons set for 500 mb 35 days after release as an initially uniform distribution. 8192 balloons released and still aloft.
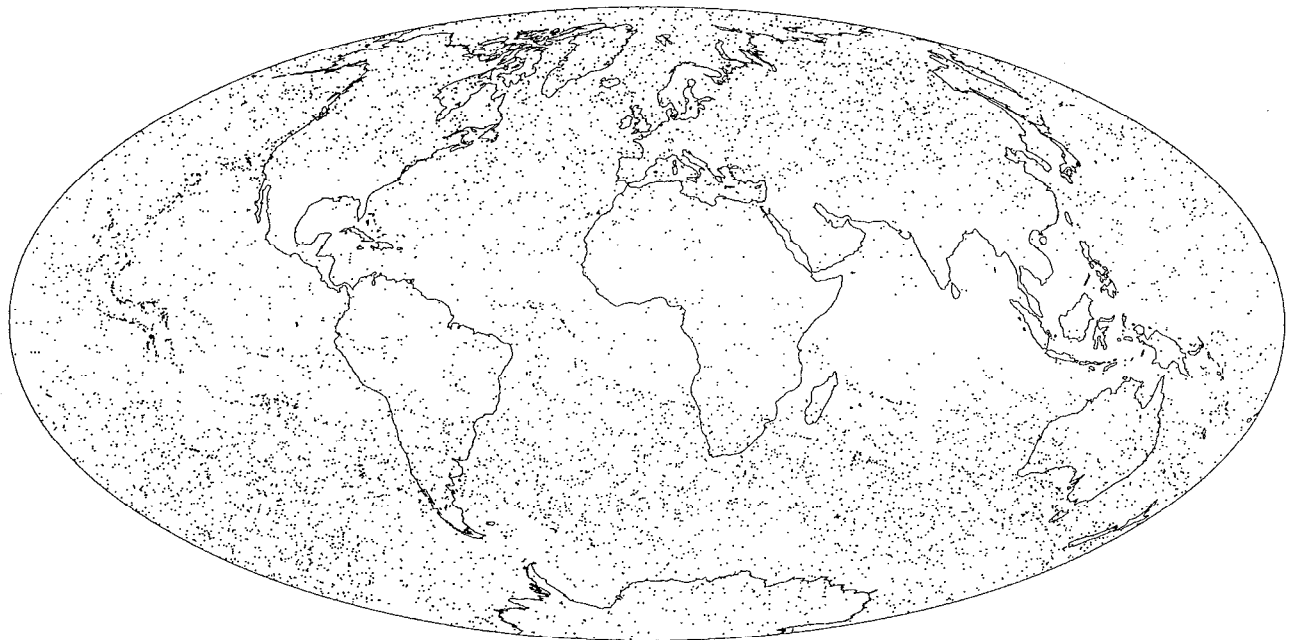
Figure 19. Location of balloons set for 400 mb 35 days after release as an initially uniform distribution. 8192 balloons released and still aloft.

Figure 20. Location of balloons set for 300 mb 35 days after release as an initially uniform distribution. 8192 balloons released and still aloft.

Figure 22. Location of balloons set for 100 mb 35 days after release as an initially uniform distribution. 8192 balloons released and still aloft.
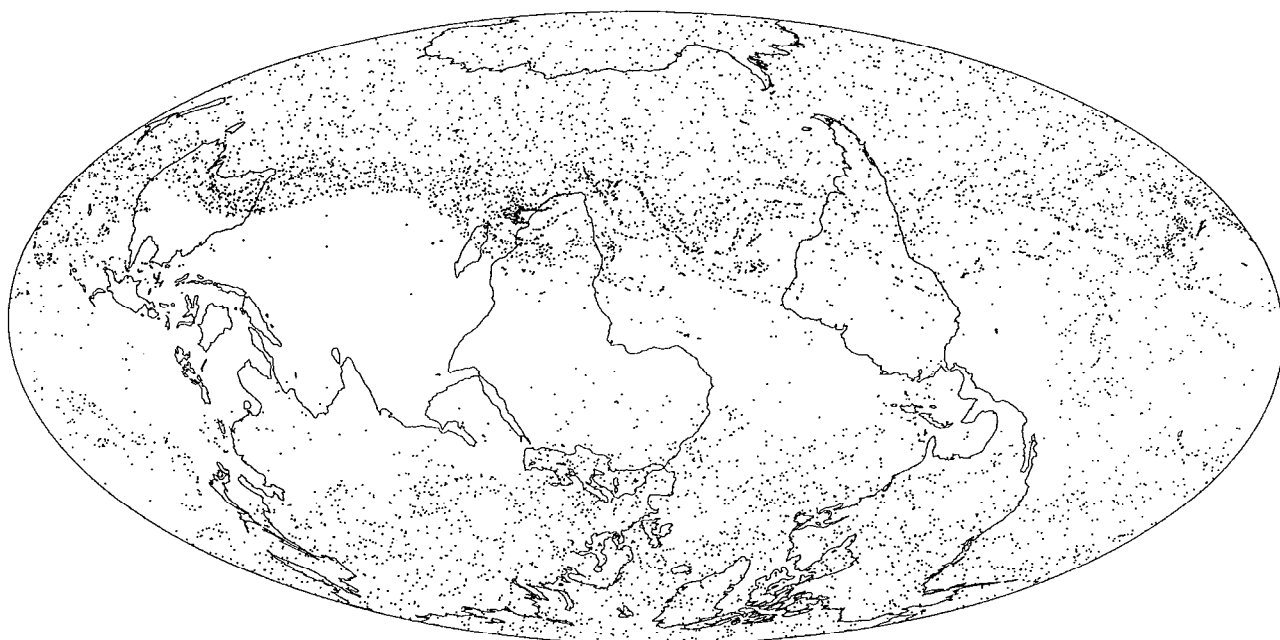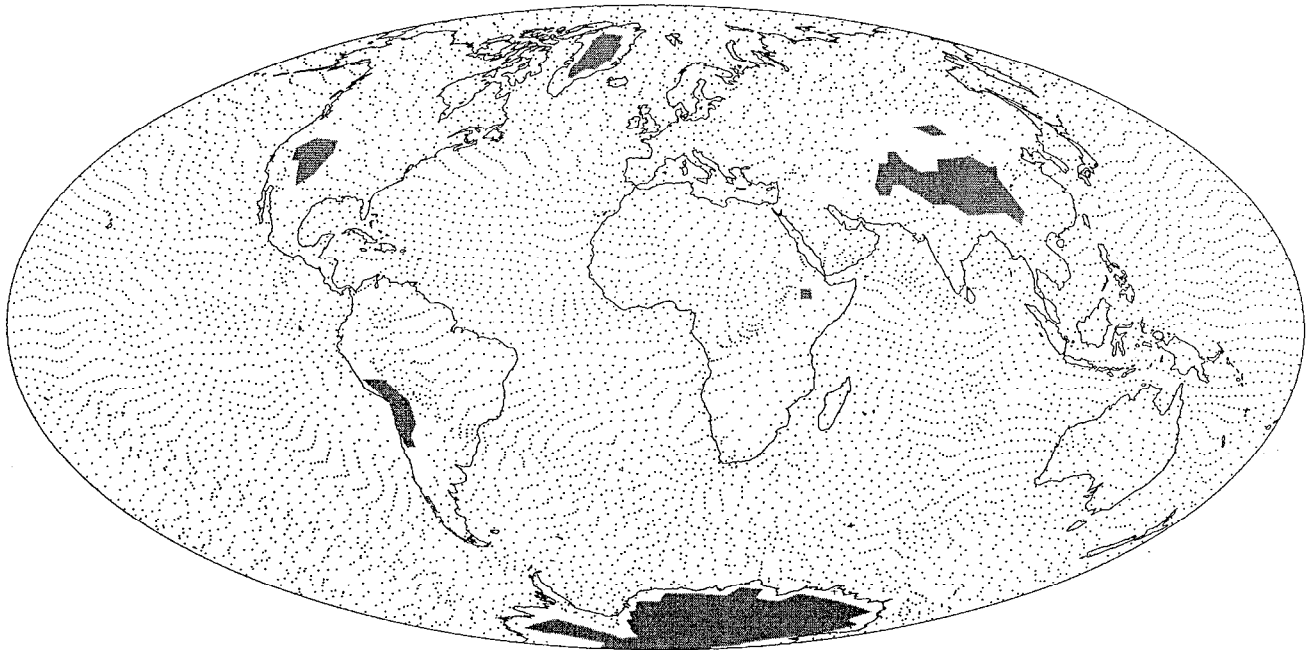

Figure 21. Location of balloons set for 200 mb 35 days after release as an initially uniform distribution. 8192 balloons released and still aloft.
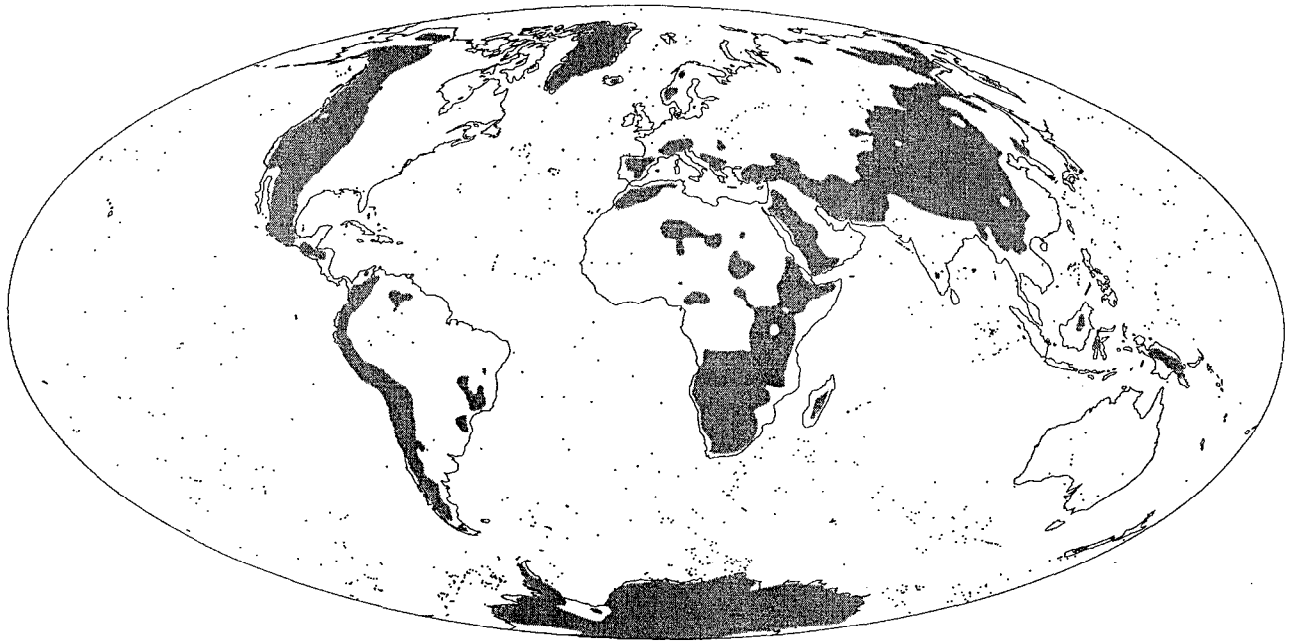
Figure 23. Location of balloons set for 925 mb 47 days after release as an initially uniform distribution. Terrain above 925 mb is shaded in gray. 7257 balloons released, 1508 still aloft, 5749 hit terrain.

Figure 24. Location of balloons set for 850 mb 47 days after release as an initially uniform distribution. Terrain above 850 mb is shaded in gray. 7739 balloons released, 3729 still aloft, 4010 hit terrain.

Figure 25. Location of balloons set for 775 mb 47 days after release as an initially uniform distribution. Terrain above 775 mb is shaded in gray. 7933 balloons released, 5741 still aloft, 2192 hit terrain.

Figure 26. Location of balloons set for 700 mb 47 days after release as an initially uniform distribution. Terrain above 700 mb is shaded in gray. 8030 balloons released, 6771 still aloft, 1259 hit terrain.

Figure 27. Location of balloons set for 600 mb 47 days after release as an initially uniform distribution. Terrain above 600 mb is shaded in gray. 8157 balloons released, 7650 still aloft, 507 hit terrain.

Figure 28. Location of balloons set for 500 mb 47 days after release as an initially uniform distribution. 8192 balloons released and still aloft.

Figure 29. Location of balloons set for 400 mb 47 days after release as an initially uniform distribution. 8192 balloons released and still aloft.

Figure 30. Location of balloons set for 300 mb 47 days after release as an initially uniform distribution. 8192 balloons released and still aloft.

Figure 31. Location of balloons set for 200 mb 47 days after release as an initially uniform distribution. 8192 balloons released and still aloft.

Figure 32. Location of balloons set for 100 mb 47 days after release as an initially uniform distribution. 8192 balloons released and still aloft.

run almost the entire length of South America in Figure 13 while they cover only the middle half of the continent in Figure 3, and the Zagros Mountains extend from the Persian Gulf in Iran to Turkey in Figure 14 while they are completely missing in Figure 4. Comparison of the balloon release and aloft data in Table 3 reveals that the higher terrain in the NOGAPS simulation causes a small decrease in the number of balloons released and a greatly enhanced attrition rate due to terrain collisions. After 47 days at a floating-level pressure of 925 mb only 1508 balloons are still aloft; clearly low level transponders must be replaced often.

The main conclusions of the CCM3/GRANTOUR simulation are confirmed by this calculation. At 925 mb the coverage is very poor. Over 70 per cent of the released balloons have been lost by collisions with terrain. In addition convergence/divergence patterns in the flow produce small areas and lines with very many balloons, clusters, and ribbons, and vast areas with almost no balloons. Comparison of the 35 day and 47 day locations illustrate the movement of these clusters and ribbons from day to day. At 850 mb the coverage is much better, and balloons remain spread over much of the globe. However, regions downwind of the mountains and some tropical areas have sparse coverage. The global distribution at mid-troposphere levels is quite good, especially at 600, 500, and 400 mb; however, there are some sparse areas in the tropics. Top of the troposphere divergence produces large areas in the tropics with very few balloons. These sparse areas terminate sharply, particularly in the southern hemisphere, along a line where balloon density is high, and this boundary meanders with time.

Comparison of Figures 13-22 at 35 days with Figures 23-32 at 47 days reveals little worsening in the global balloon distributions except the additional loss of balloons via terrain collisions, i.e., most of the deterioration occurred earlier. Early temporal decay of the initially uniform distribution is shown by the balloon location plots for days 1, 2, 3, 4, 5, 7, 10, and 15 at 850 mb in Figures 33-40 and at 200 mb in Figures 41-48. By two or three days any sense of regularity in the release pattern has disappeared. Within one week one sees significant regions where balloons have collected and where they have left. By two weeks the main features and deficiencies noted at the end of the runs are already evident. The rate at which upper level (200 mb) balloons leave the tropical Indian Ocean area is amazing; this characteristic shows up for both CCM3 and NOGAPS winds.

3. Vertical Sounding Coverage

While the three-dimensional spacing of transponders is the primary issue, an additional question is the feasibility of measuring atmospheric vertical profiles of wind and temperature at enough points to provide input for NWP's. This has particular relevance to early deployment of a degraded transponder network to provide input to current NWP's which have much better capabilities for assimilating column or sounding data than randomly spaced observations. This question can be addressed by dividing the atmosphere into uniform vertical columns and then counting the number of floating-level layers within each column that contain at least one balloon. By selecting a column size correlated with a NWP's horizontal resolution and assuming some minimum number of occupied vertical layers for an adequate sounding, one can estimate the
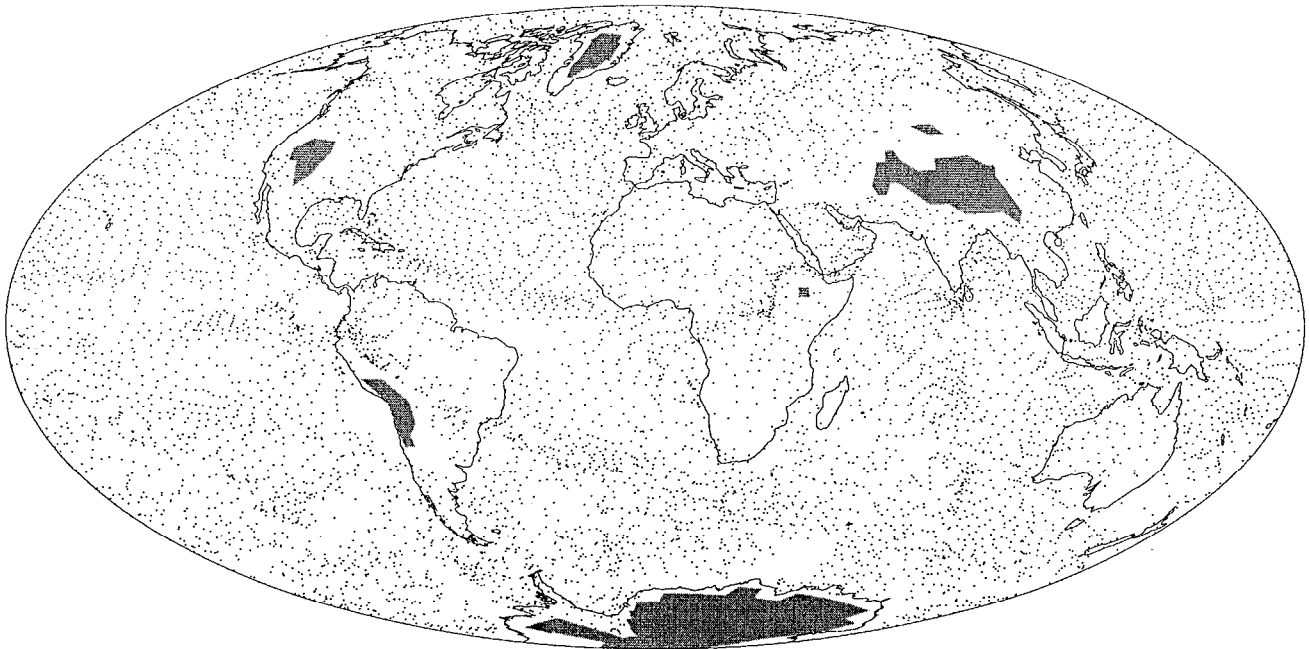
Figure 33. Location of balloons set for 850 mb 1 day after release as an initially uniform distribution. Terrain above 850 mb is shaded in gray. 7862 balloons released, 7791 still aloft, 71 hit terrain.
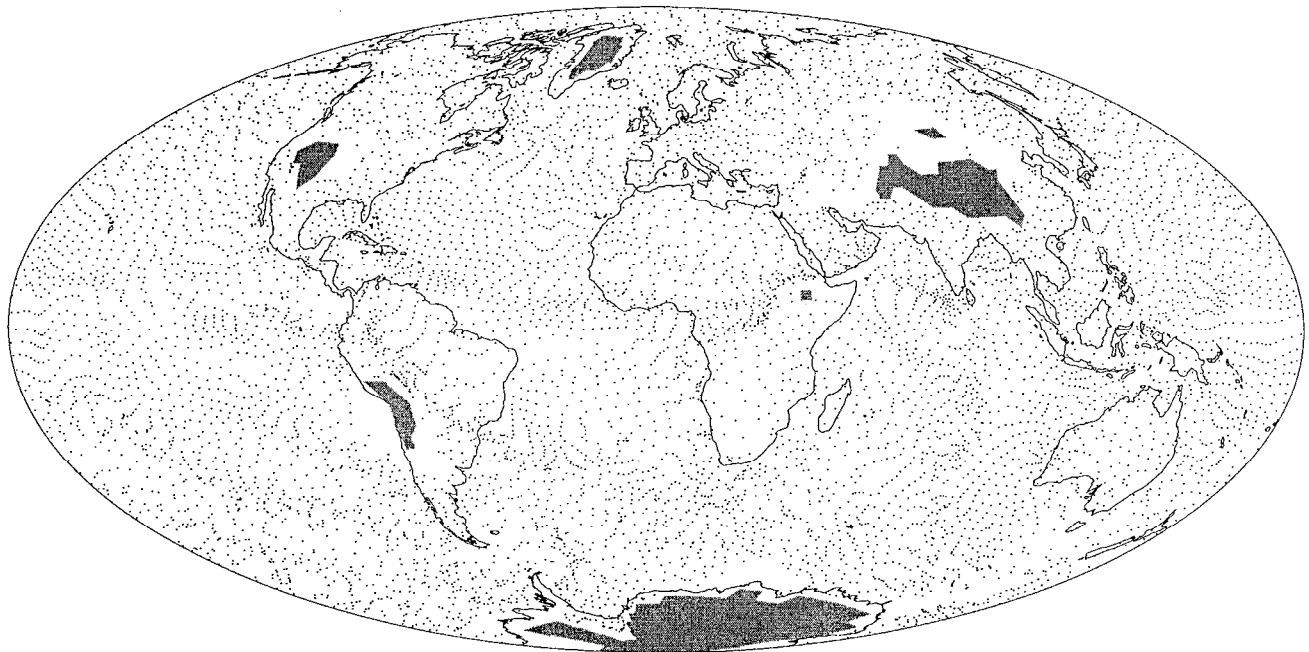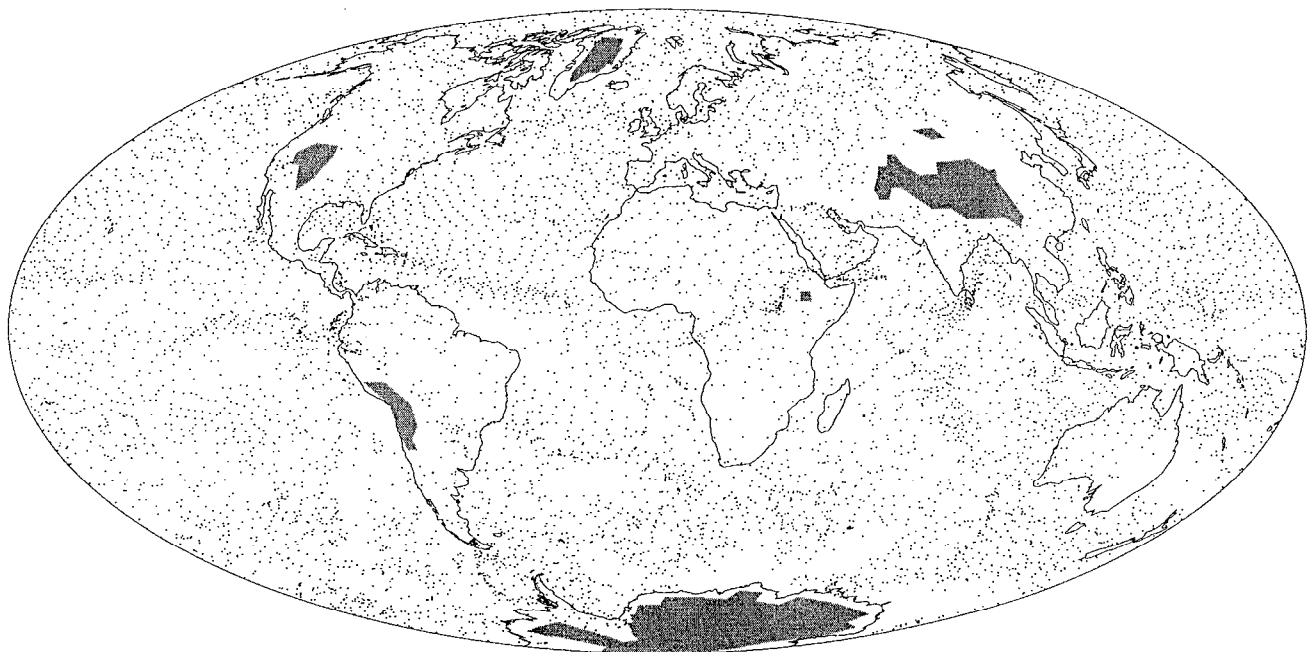

Figure 34. Location of balloons set for 850 mb 2 days after release as an initially uniform distribution. Terrain above 850 mb is shaded gray. 7862 balloons released, 7729 still aloft, 133 hit terrain.
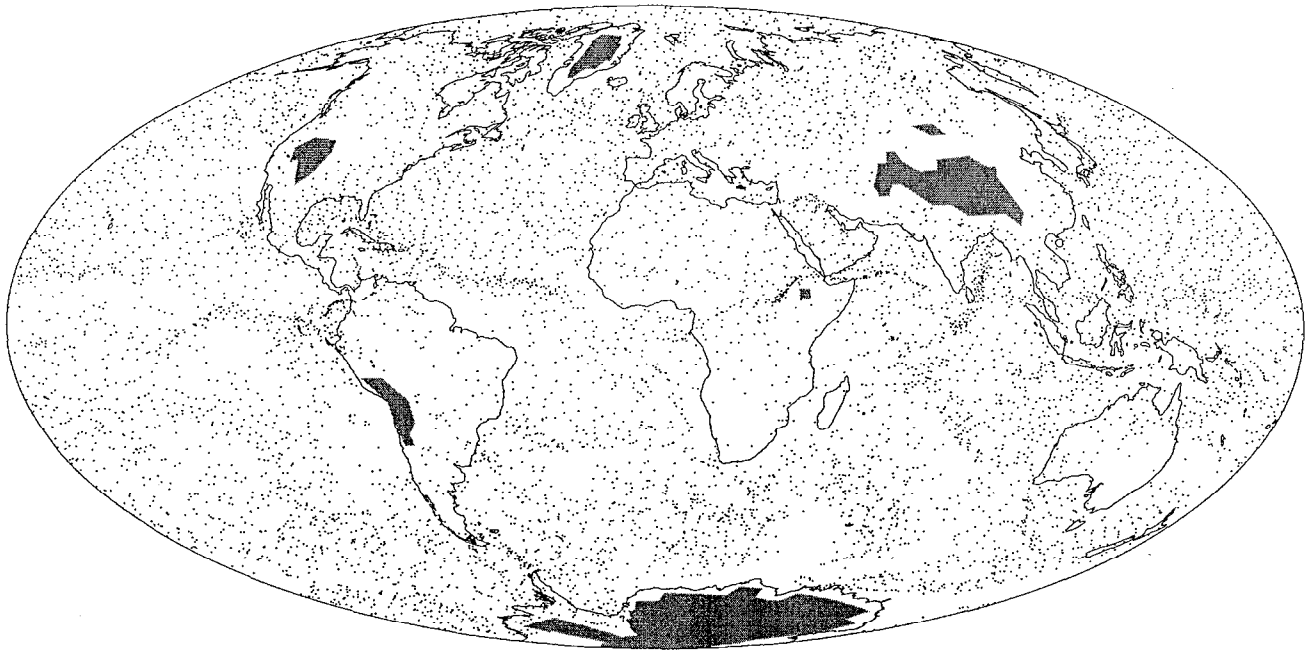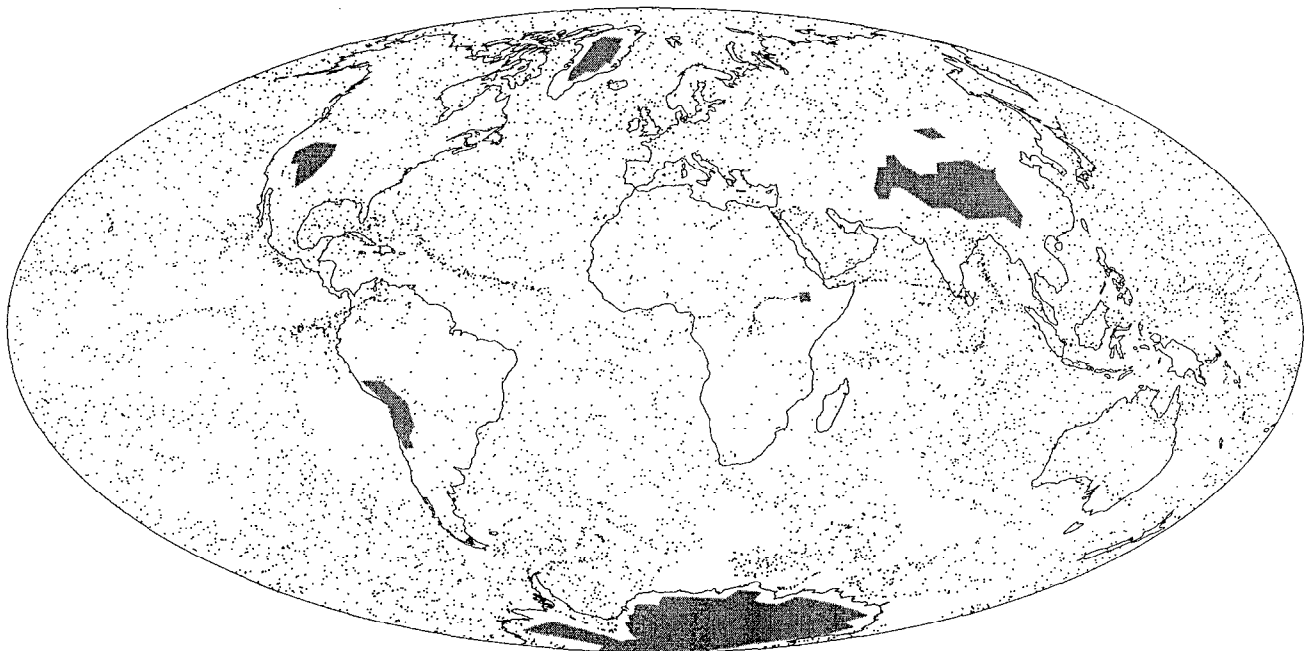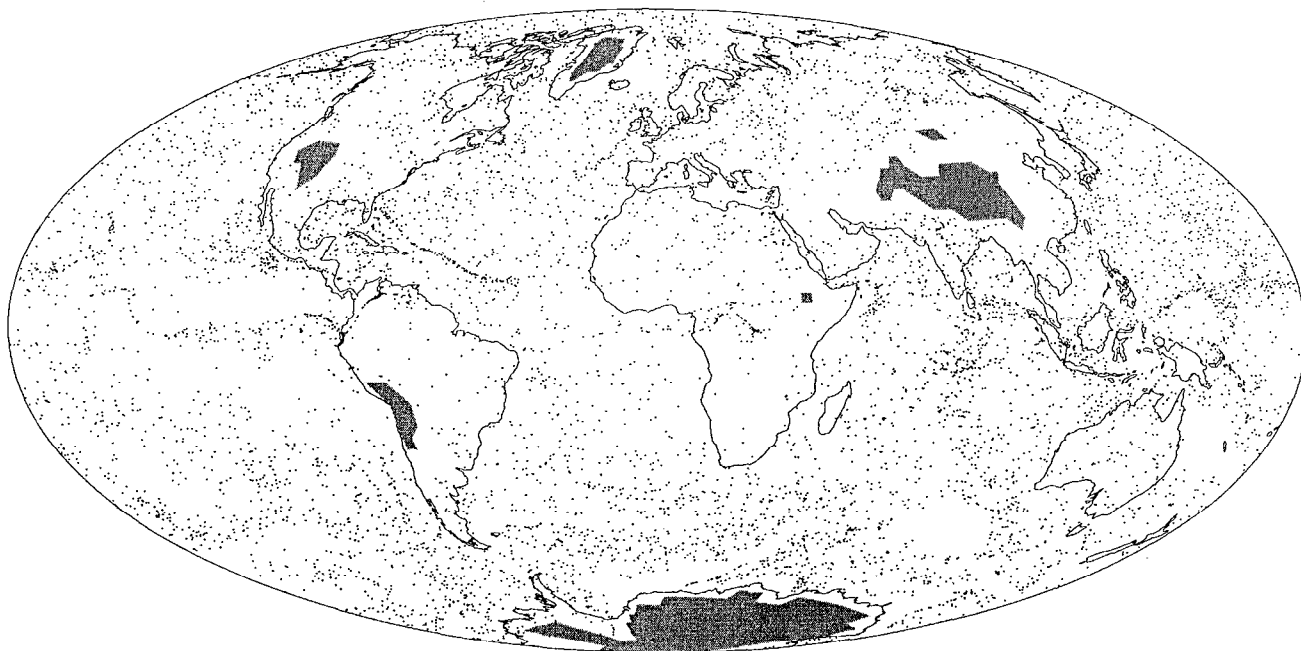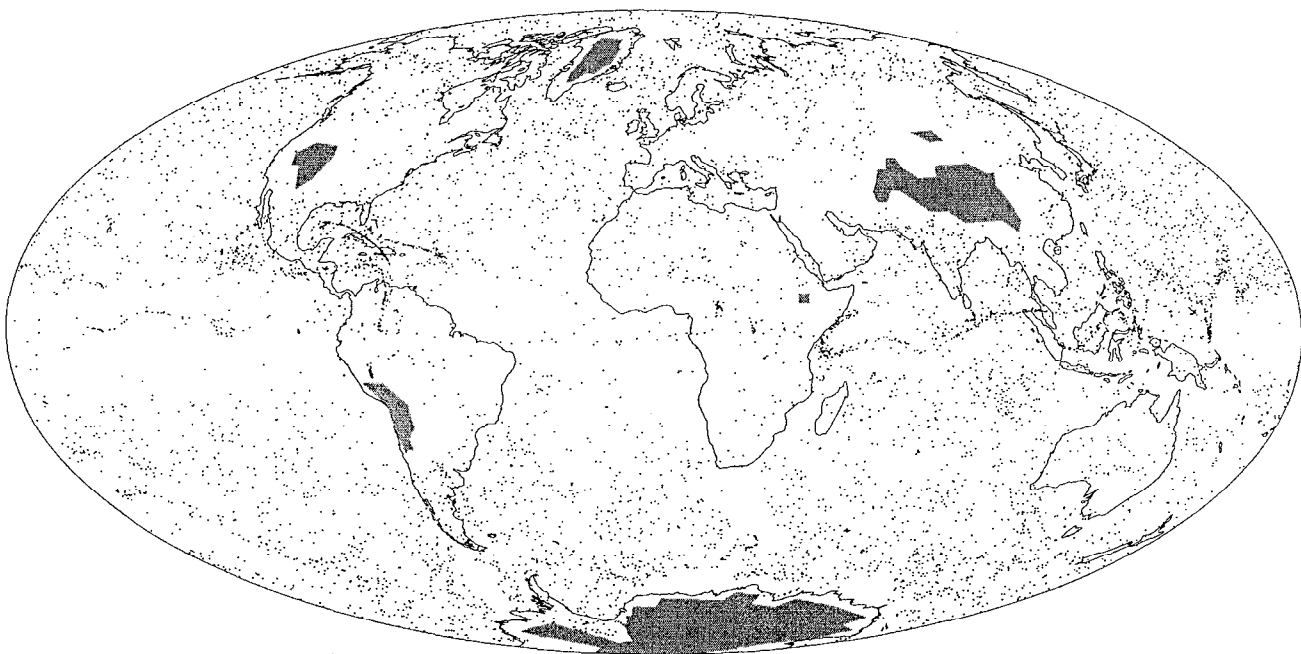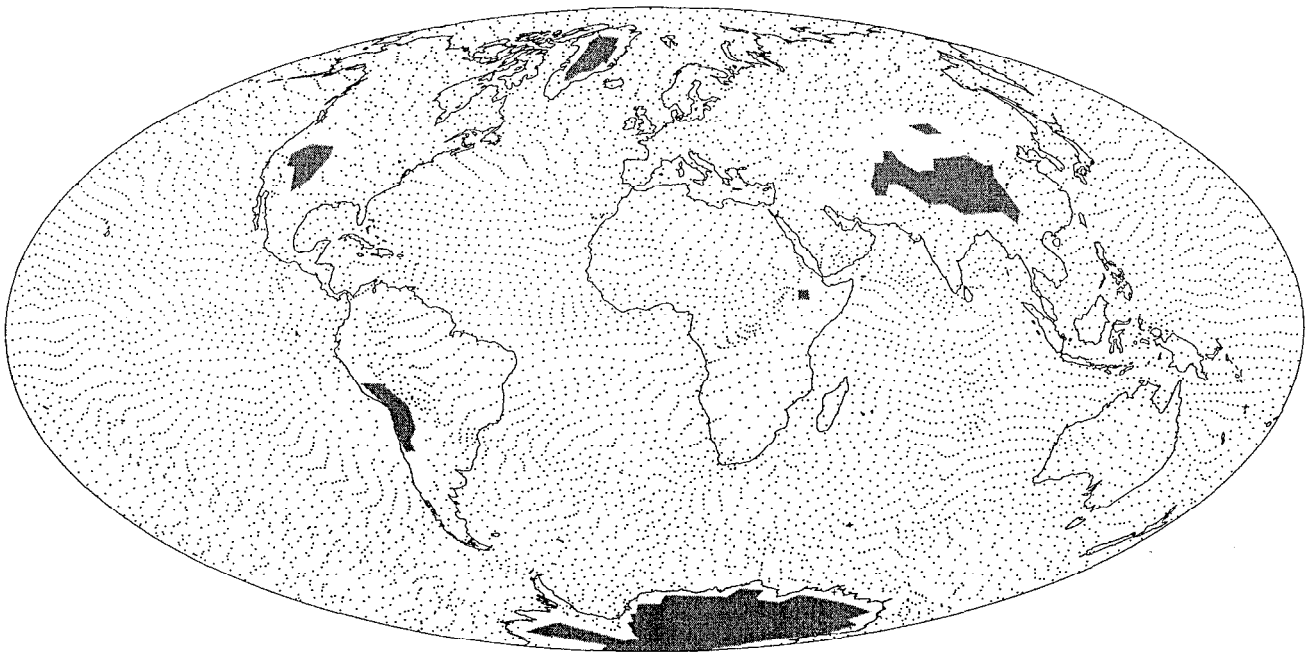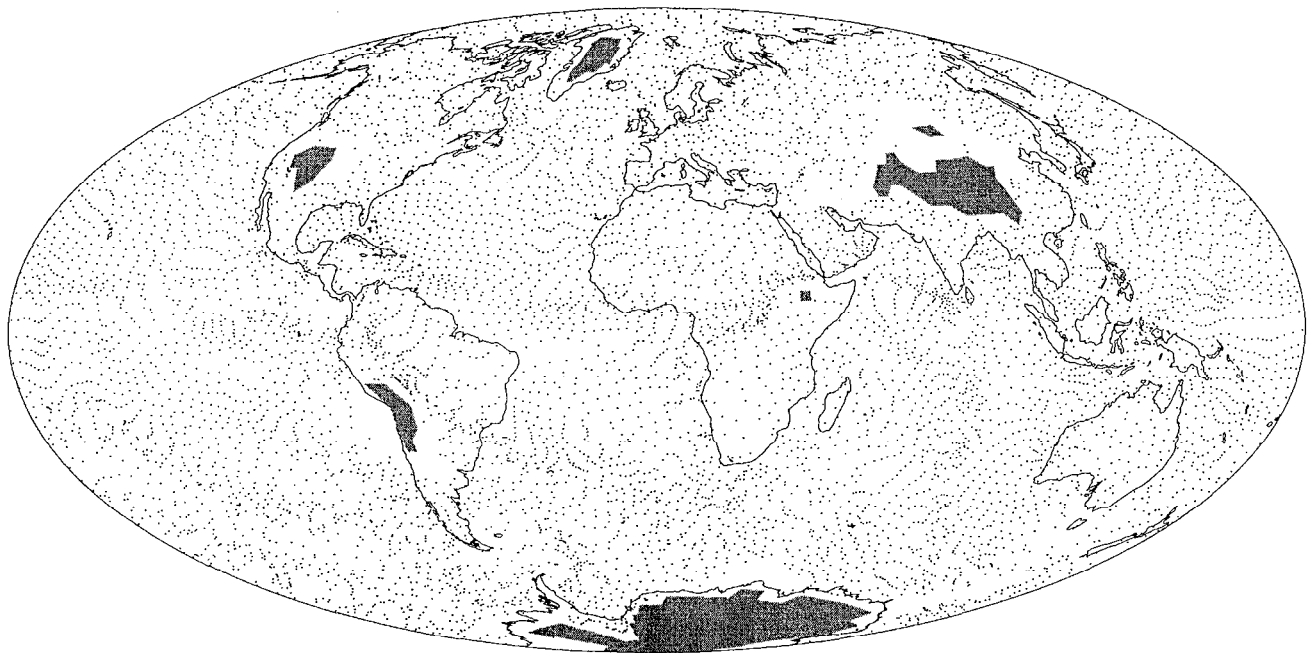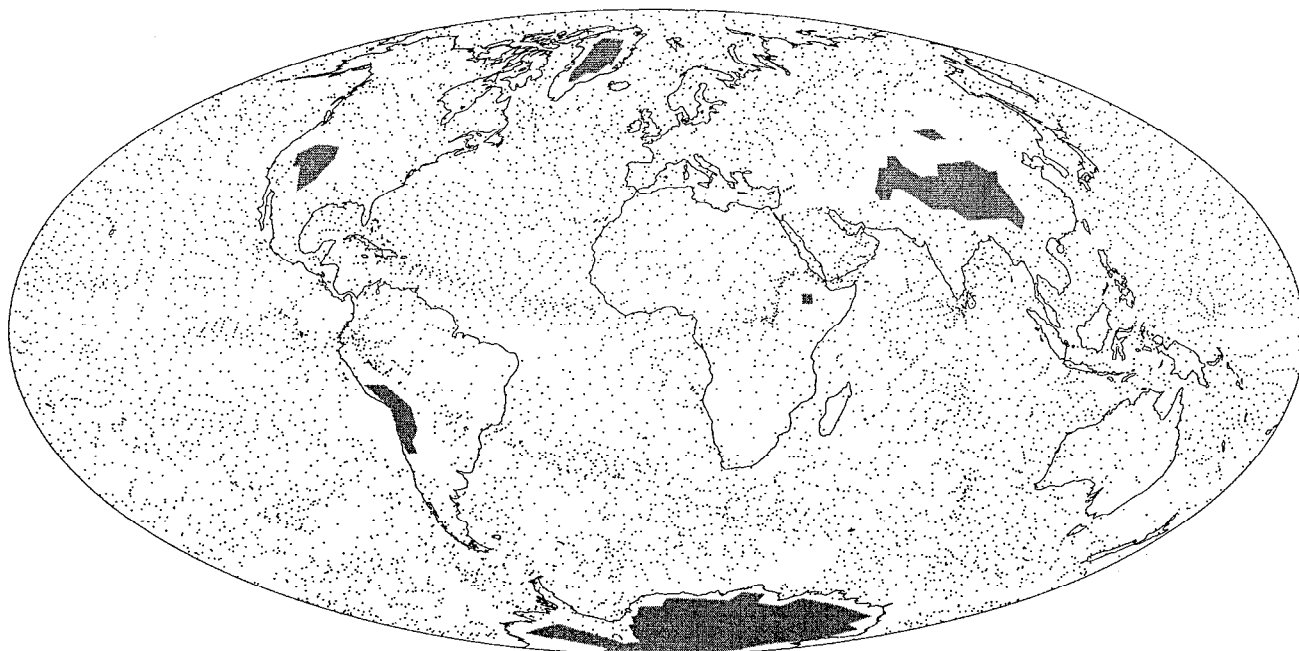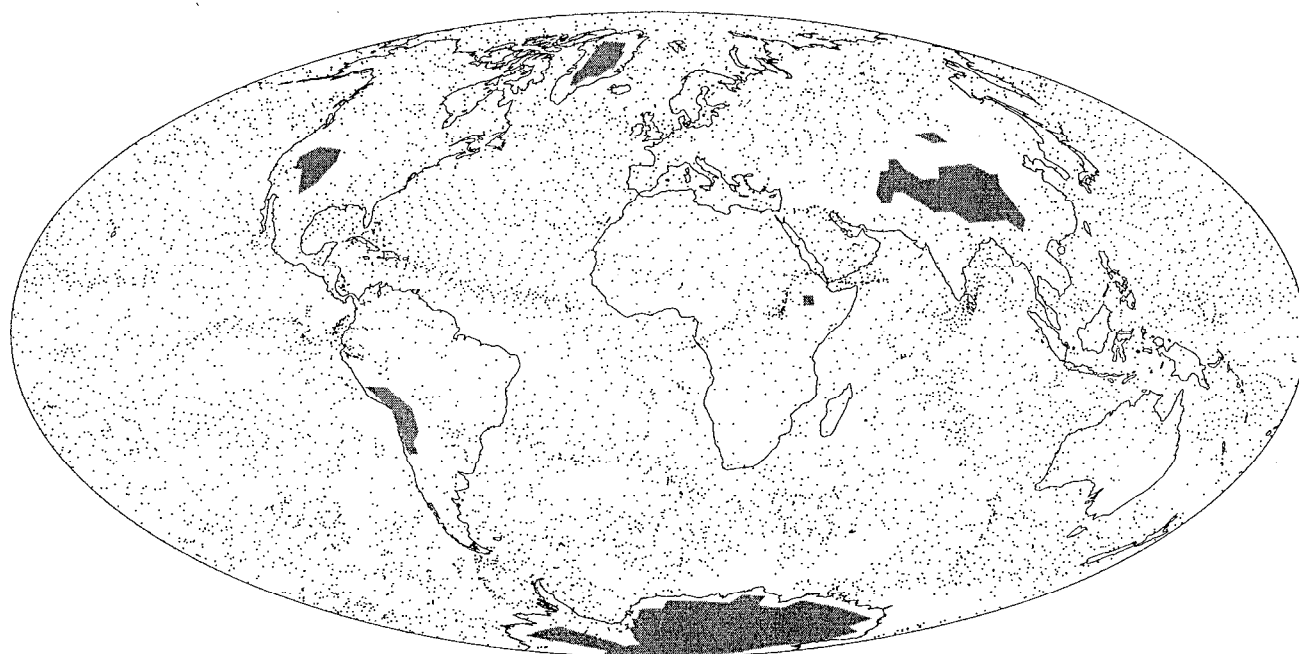
28

Figure 35. Location of balloons set for 850 mb 3 days after release as an initially uniform distribution. Terrain above 850 mb is shaded gray. 7862 balloons released, 7676 still aloft, 186 hit terrain.
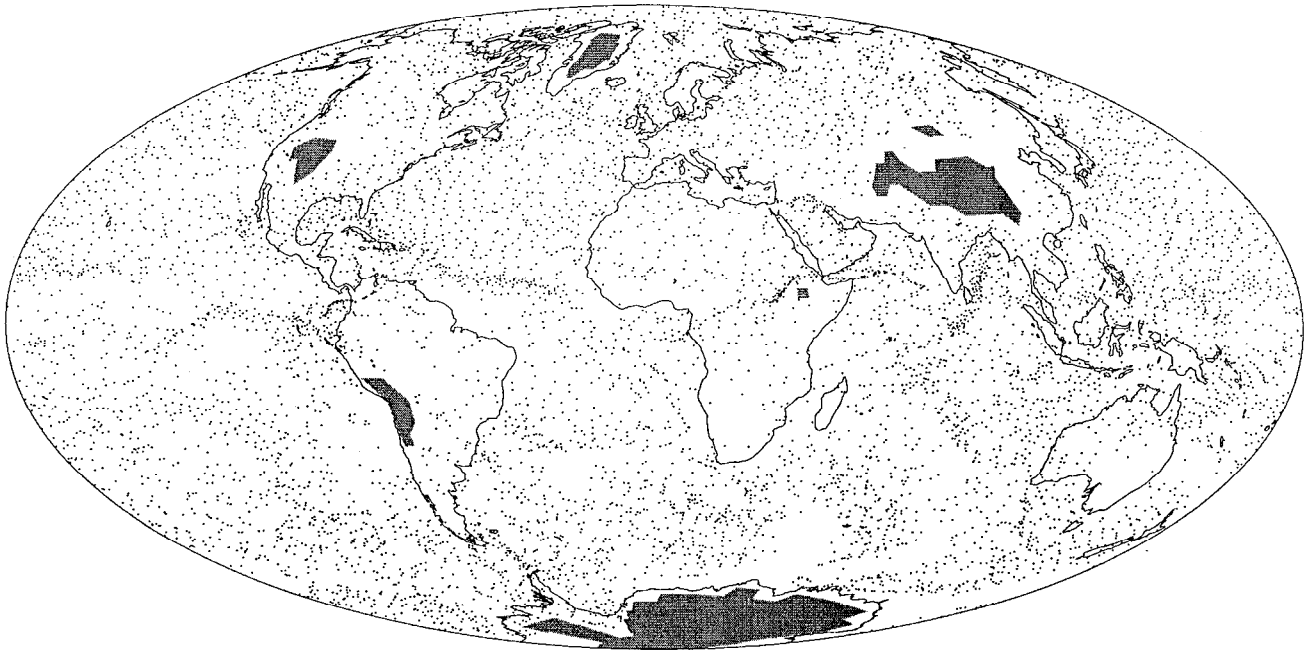

Figure 36. Location of balloons set for 850 mb 4 days after release as an initially uniform distribution. Terrain above 850 mb is shaded gray. 7862 balloons released, 7651 still aloft, 211 hit terrain.
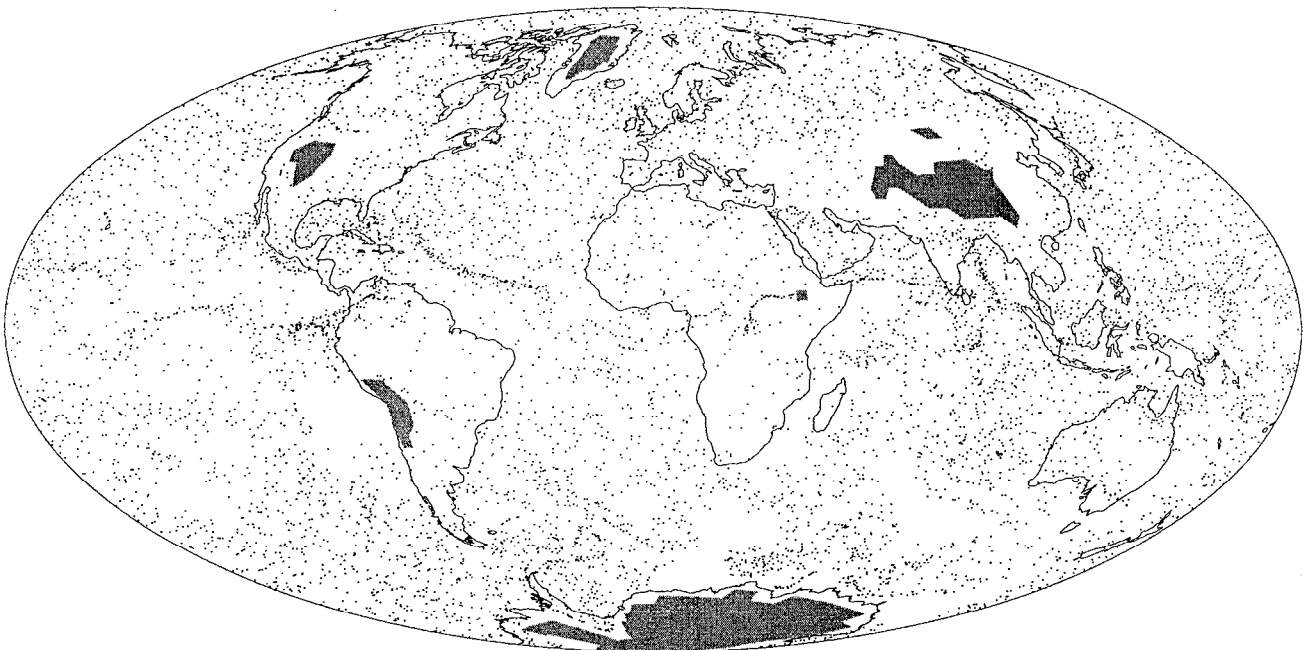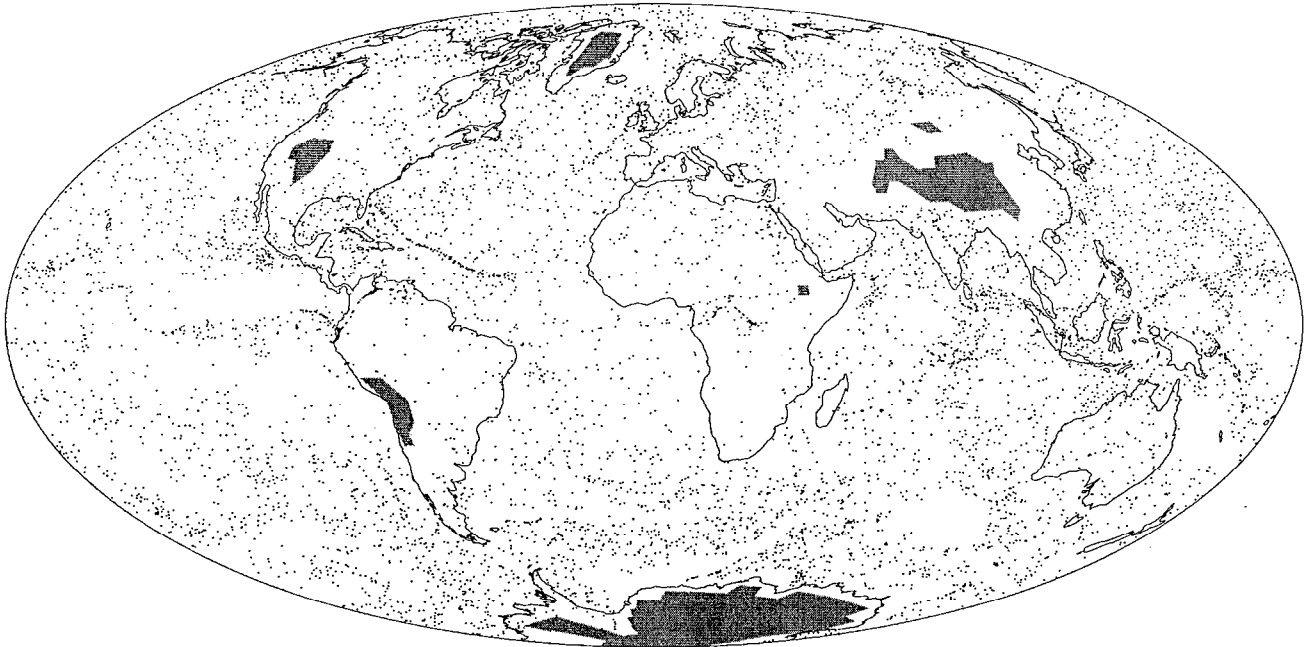
Figure 37. Location of balloons set for 850 mb 5 days after release as an initially uniform distribution. Terrain above 850 mb is shaded in gray. 7862 balloons released, 7613 still aloft, 249 hit terrain.

Figure 38. Location of balloons set for 850 mb 7 days after release as an initially uniform distribution. Terrain above 850 mb is shaded in gray. 7862 balloons released, 7533 still aloft, 329 hit terrain.

Figure 39. Location of balloons set for 850 mb 10 days after release as an initially uniform distribution. Terrain above 850 mb is shaded in gray. 7862 balloons released, 7383 still aloft, 479 hit terrain.
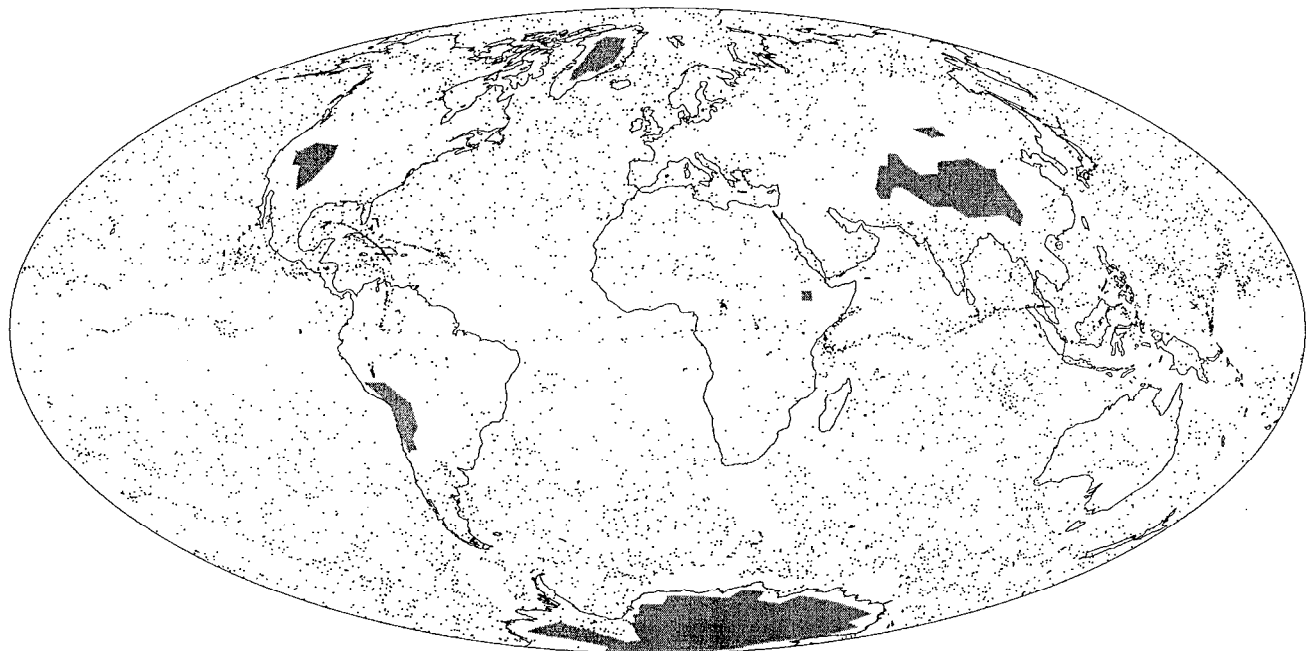

Figure 40. Location of balloons set for 850 mb 15 days after release as an initially uniform distribution. Terrain above 850 mb is shaded in gray. 7862 balloons released, 7241 still aloft, 621 hit terrain.

Figure 41. Location of balloons set for 850 mb 1 day after release as an initially uniform distribution. Terrain above 850 mb is shaded in gray. 7862 balloons released, 7791 still aloft, 71 hit terrain.

Figure 42. Location of balloons set for 850 mb 2 days after release as an initially uniform distribution. Terrain above 850 mb is shaded gray. 7862 balloons released, 7729 still aloft, 133 hit terrain.

Figure 43. Location of balloons set for 850 mb 3 days after release as an initially uniform distribution. Terrain above 850 mb is shaded gray. 7862 balloons released, 7676 still aloft, 186 hit terrain.

Figure 44. Location of balloons set for 850 mb 4 days after release as an initially uniform distribution. Terrain above 850 mb is shaded gray. 7862 balloons released, 7651 still aloft, 211 hit terrain.

Figure 45. Location of balloons set for 850 mb 5 days after release as an initially uniform distribution. Terrain above 850 mb is shaded in gray. 7862 balloons released, 7613 still aloft, 249 hit terrain.

Figure 46. Location of balloons set for 850 mb 7 days after release as an initially uniform distribution. Terrain above 850 mb is shaded in gray. 7862 balloons released, 7533 still aloft, 329 hit terrain.

Figure 47.Location of balloons set for 850 mb 10 days after release as an initially uniform distribution. Terrain above 850 mb is shaded in gray. 7862 balloons released, 7383 still aloft, 479 hit terrain.

Figure 48. Location of balloons set for 850 mb 15 days after release as an initially uniform distribution. Terrain above 850 mb is shaded in gray. 7862 balloons released, 7241 still aloft, 621 hit terrain.

adequacy of a transponder network. The number of vertical layers per horizontal column with at least one balloon is plotted in Figures 49-54. In these plots warmer colors (yellow, orange, and red) mark areas with larger numbers of occupied layers, and cooler colors (blue, purple, and black) mark areas with fewer occupied layers. If we assume a vertical profile is defined when six or more layers provide wind and temperature data, we see that few areas have adequate transponders especially in the higher horizontal resolution cases (Figures 49, 51, and 53). Mid-latitude columns generally have more occupied layers, but the predominance of blue and purple in the tropics confirms the earlier result that too few transponders remain there. Note, however, that regions of high topography, such as the south pole and the Himalayas, have only five to seven floating-levels above terrain; so, fewer occupied layers are required to define a vertical profile.

Major conclusions from the uniform distribution simulations include the following: Balloons quickly leave the tropics especially at low altitudes and near the tropopause. Low altitude transponders frequently run into terrain; any operational program would have to replace these balloons often. Predominantly zonal flow makes it possible to maintain an adequate transponder density in mid-latitudes and near the poles.

B. Daily Release Scenario

1. CCM3/GRANTOUR

The CCM3/GRANTOUR daily release simulation ran for 35 days. At the beginning of each day a balloon was released on each of the ten floating-level pressures from 298 sites. However, a few of the 298 sites were at altitudes above some floating-level pressures so not all levels had 298 release sites. The number of release sites for each level is included in Table 4. For the floating-level pressures where terrain was not a factor, 298 balloons were present on the first day, 596 on the second, etc. At larger floating-level pressures (lower altitudes) fewer launch sites were active and balloons crashed into terrain; therefore, smaller numbers of balloons remained aloft. For example, at 925 mb 272 balloons were launched the first day, and 11 of these crashed, leaving 261. At the start of the second day 272 more were released, and 15 hit the ground during this day,

Table 4. Number of Balloons after 35 days for the CCM3/GRANTOUR Simulation

| Level	Release Sites	Released	Crashed	Aloft
100-500	298	10430	0	10430
600	297	10395	206	10189
700	295	10325	333	9992
775	292	10220	623	9597
850	288	10080	1322	8758
925	272	9520	3297	6223
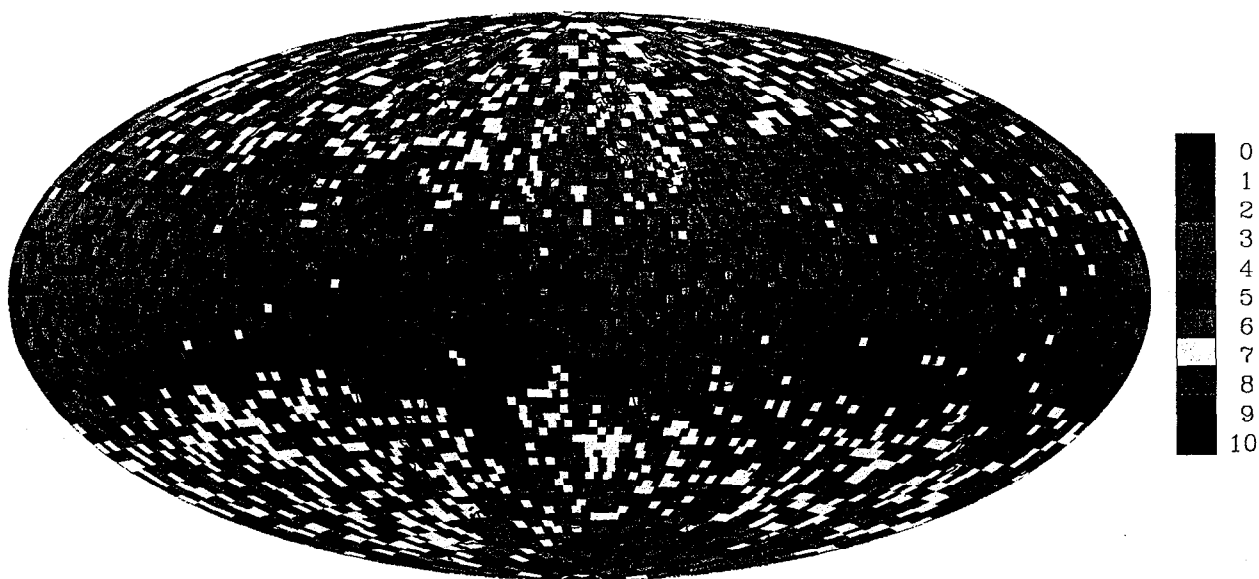
Figure 49. Number of vertical layers per horizontal column with at least 1 balloon for day 35 of the CCM3 wind data simulation starting with an initial uniform distribution. There are 80 equal area latitude bands and 8150 equal area columns of about 62,500 km² or 250 km on a side.
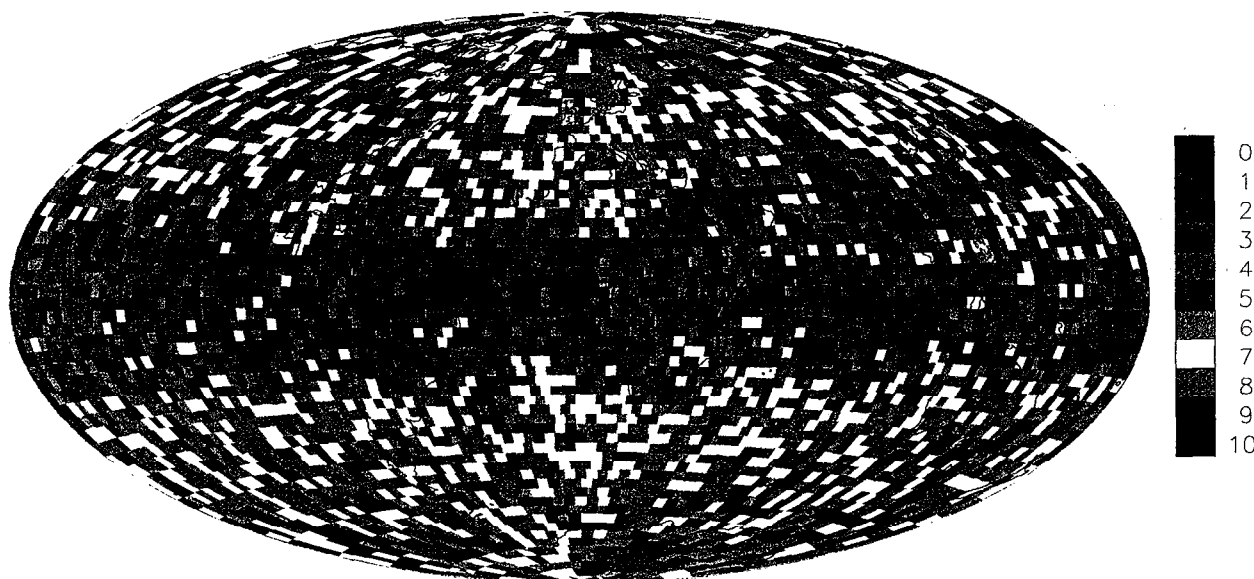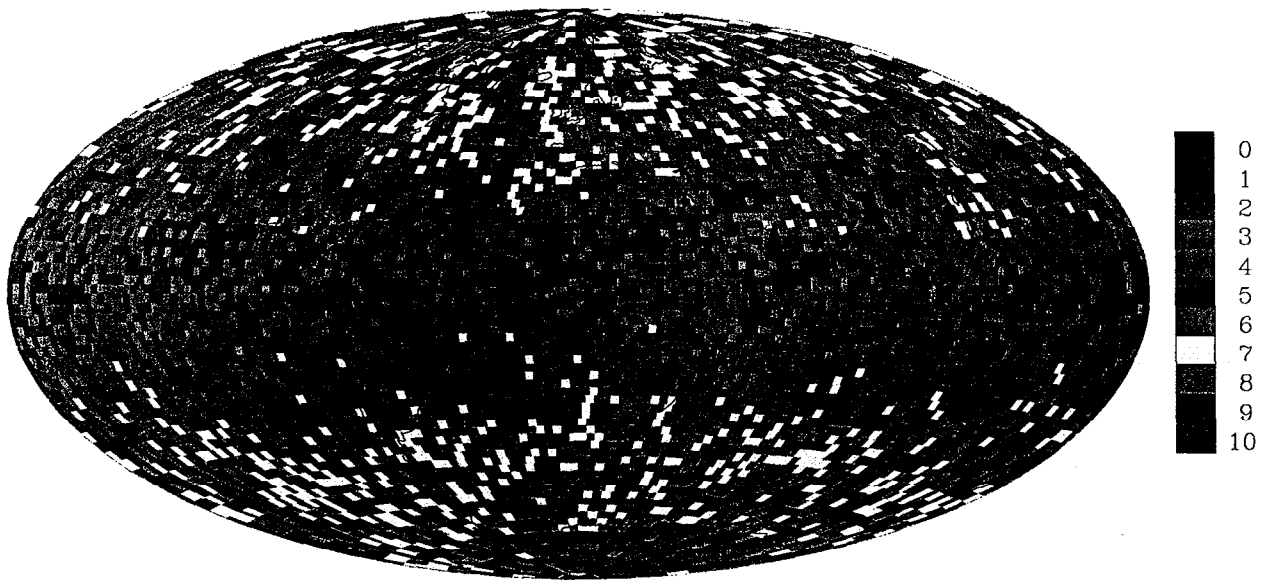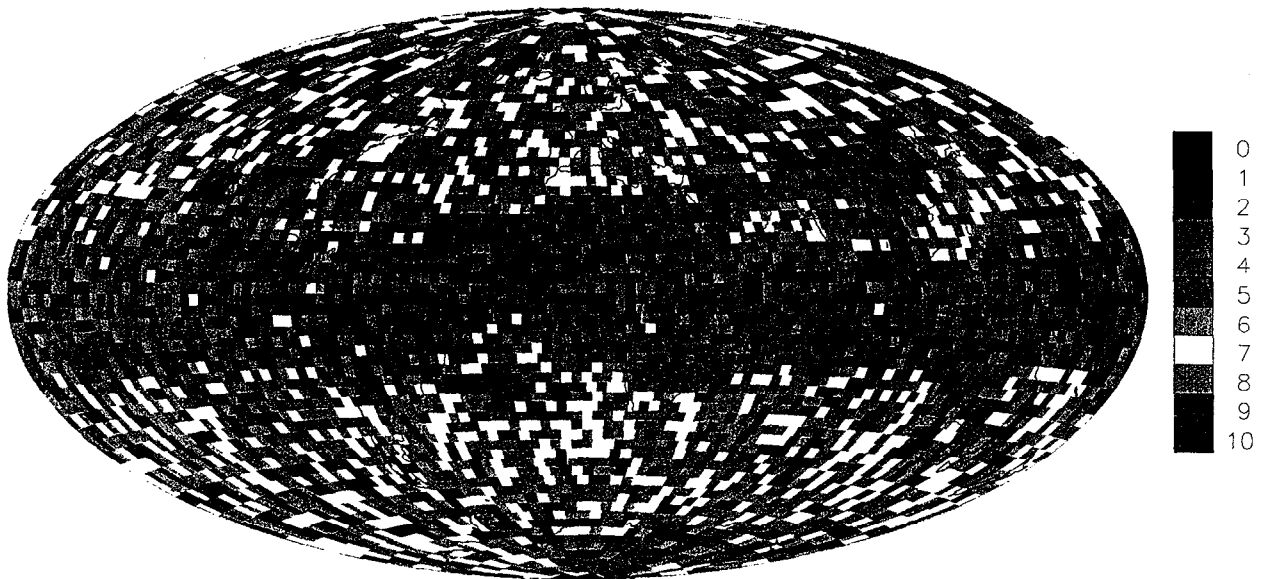

Figure 50. Number of vertical layers per horizontal column with at least 1 balloon for day 35 of the CCM3 wind data simulation starting with an initial uniform distribution. There are 64 equal area latitude bands and 5218 equal area columns of about 98,000 km² or 313 km on a side.
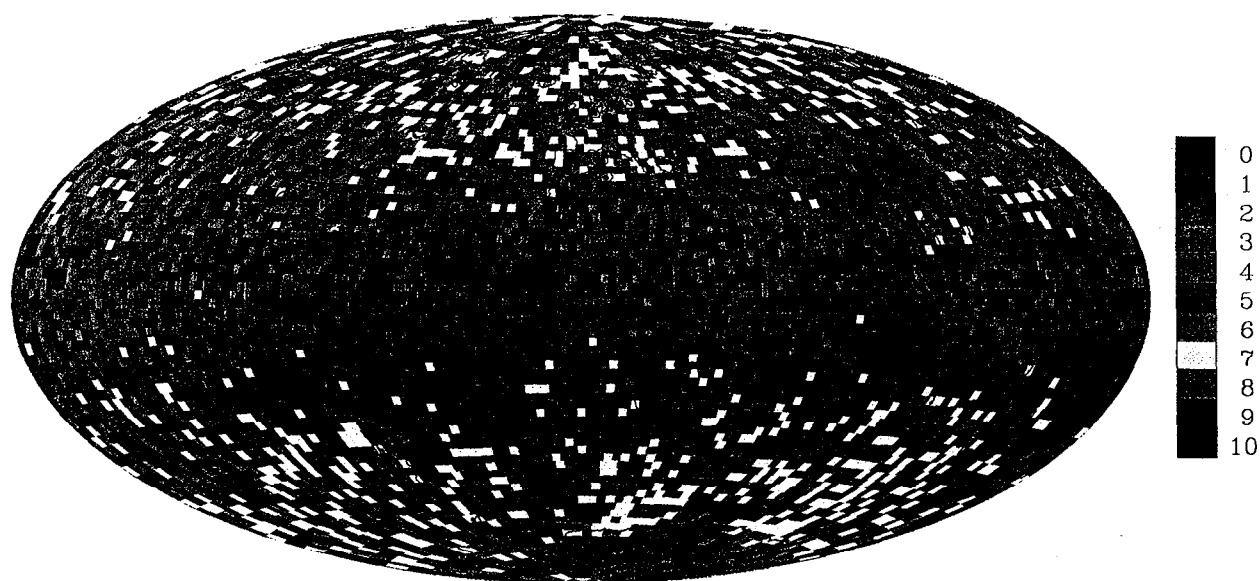
Figure 51. Number of vertical layers per horizontal column with at least 1 balloon for day 35 of the NOGAPS wind data simulation starting with an initial uniform distribution. There are 80 equal area latitude bands and 8150 equal area columns of about 62,500 km² or 250 km on a side.
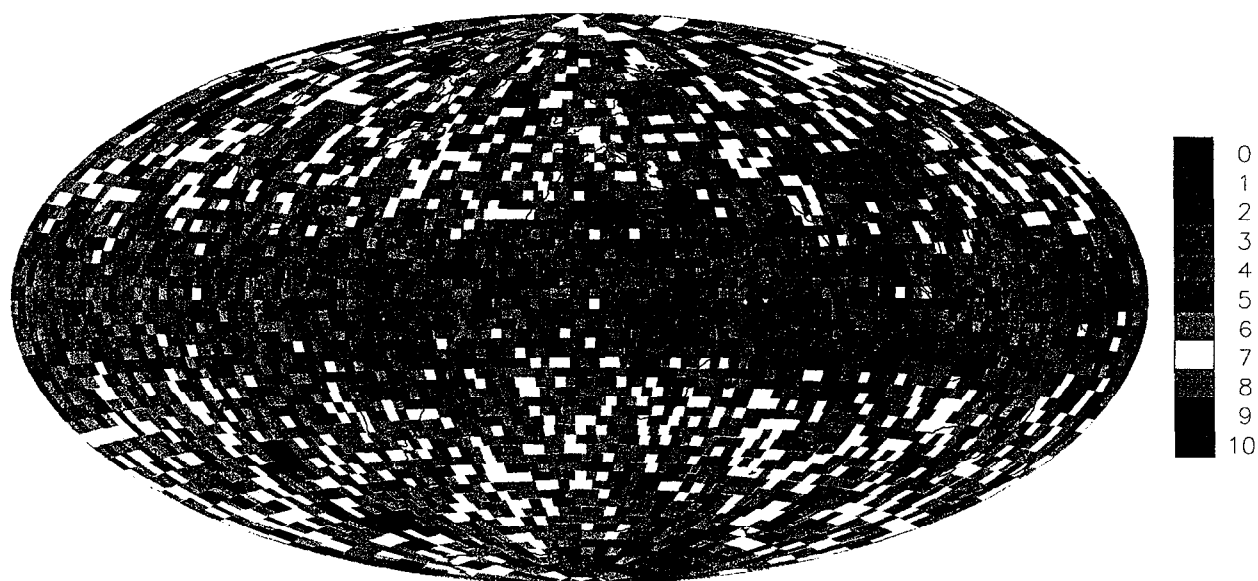
Figure 52. Number of vertical layers per horizontal column with at least 1 balloon for day 35 of the NOGAPS wind data simulation starting with an initial uniform distribution. There are 64 equal area latitude bands and 5218 equal area columns of about 98,000 km² or 313 km on a side.

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Figure 53. Number of vertical layers per horizontal column with at least 1 balloon for day 47 of the NOGAPS wind data simulation starting with an initial uniform distribution. There are 80 equal area latitude bands and 8150 equal area columns of about 62,500 km² or 250 km on a side.

Figure 54. Number of vertical layers per horizontal column with at least 1 balloon for day 47 of the NOGAPS wind data simulation starting with an initial uniform distribution. There are 64 equal area latitude bands and 5218 equal area columns of about 98,000 km² or 313 km on a side.

leaving 518. On the third day, 272 more were launched, and 32 crashed, leaving 758 aloft after three days. On the 35th day the last 272 balloons were released, 135 balloons crashed, and 6223 were still aloft. In the daily release simulation 65 per cent of the released balloons were still aloft at the end of the run compared with 46 per cent in the uniform distribution run. More balloons are left aloft in the daily release scenario because their average age is smaller and they have less time to crash into the mountains.

Locations of the active transponders after 35 days are shown in Figures 55-64. Comparing these plots with the uniform distribution run (Figures 3-12) reveals a very noticeable improvement in global coverage. Much of the improvement is due to continual release of balloons in regions where airflow divergence removes transponders. In addition, some improvement is due to a larger number of active balloons (10430 vs. 8192 for layers above terrain). Finally, for levels close to the surface (925 and 850 mb), a larger fraction of the released transponders is still active at the end of the 35th day.

Many characteristics we pointed out in the discussion of the uniform release are present in the daily release simulation. These repeated features include convergence of balloons in several tropical areas such as central India and the Carribean, northern Arabian, and South China Seas, ribbons of balloons in the tropics and mid-latitudes, especially in the southern hemisphere, and large areas downwind of the mountains almost completely without transponders. Nevertheless, the depleted areas are smaller and not as intense as in the initial uniform distribution case.

Global coverage is worst for the layers closest to the surface (Figure 55, 925 mb) and to the tropopause (Figure 63, 200 mb). The global distribution of transponders in the rest of the atmosphere is very good. At 925 mb, wind speeds are smaller and the flow less zonal so balloons are not transported around the globe as rapidly as at higher altitudes. In the tropics especially, transponders remain close to their release points and gather in specific areas or along convergence lines. This leads to under sampling in some areas and surplus transponders in others. More and perhaps a different selection of release points would help rectify this defect.

The failure to keep sufficient transponders in the tropical tropopause region is potentially more serious. As we pointed out in the uniform distribution section, transport out of this region is rapid; after only one week most of the balloons that started here are gone. The only obvious strategy to counteract this problem is more frequent releases from more sites, perhaps using shorter lifetime balloons to prevent swamping mid-latitudes with transponders. Another possibility would be launching higher level balloons and allowing them to lose buoyancy and sink through this part or the atmosphere, but just designing small transponder carrying balloons to reach such high altitudes is already a formidable problem.
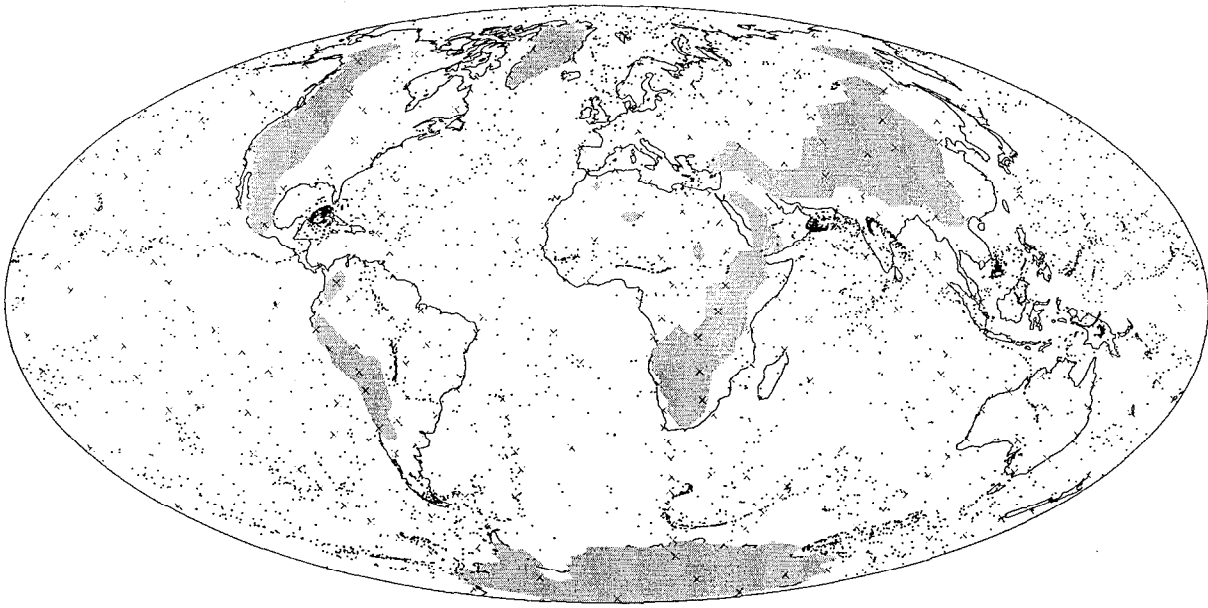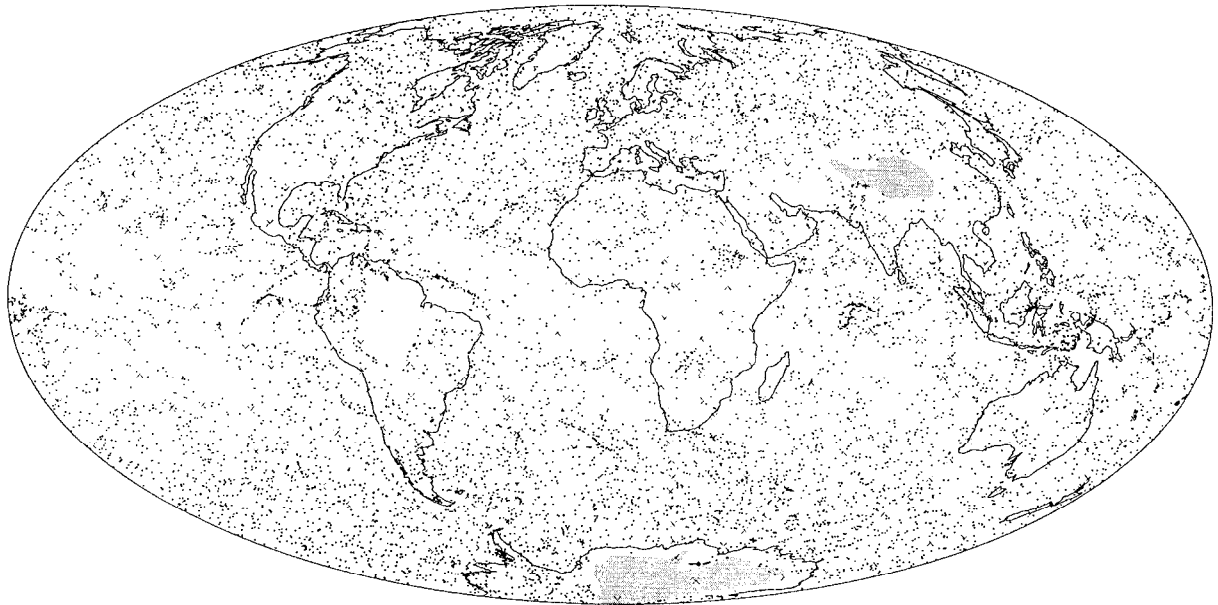
Figure 55. Location of balloons set for 925 mb after 35 days of daily releases from 298 launch sites indicated by ×. Terrain above 925 mb is shaded in gray. 9520 balloons released, 6223 still aloft, 3297 hit terrain.
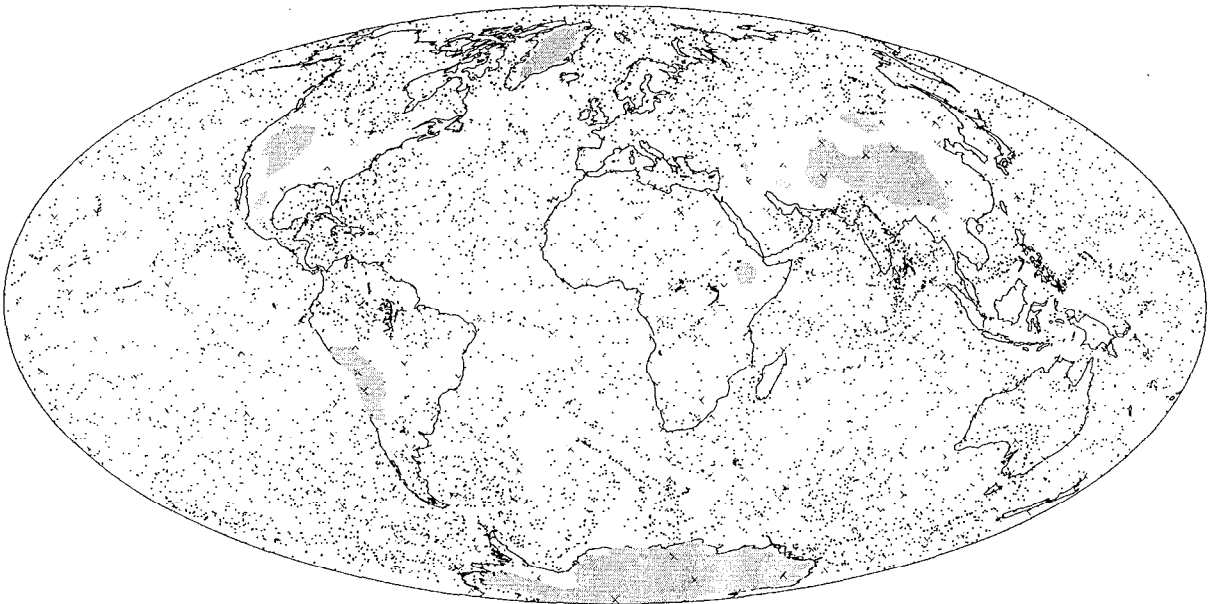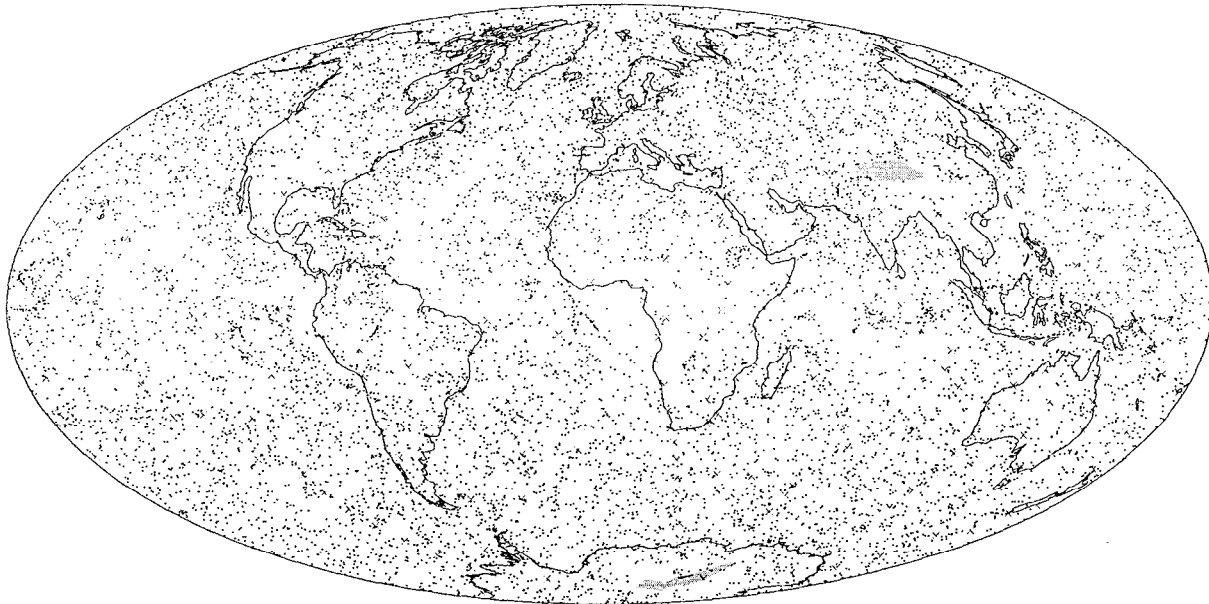

Figure 56. Location of balloons set for 850 mb after 35 days of daily releases from 298 launch sites indicated by ×. Terrain above 850 mb is shaded in gray. 10080 balloons released, 8758 still aloft, 1322 hit terrain.
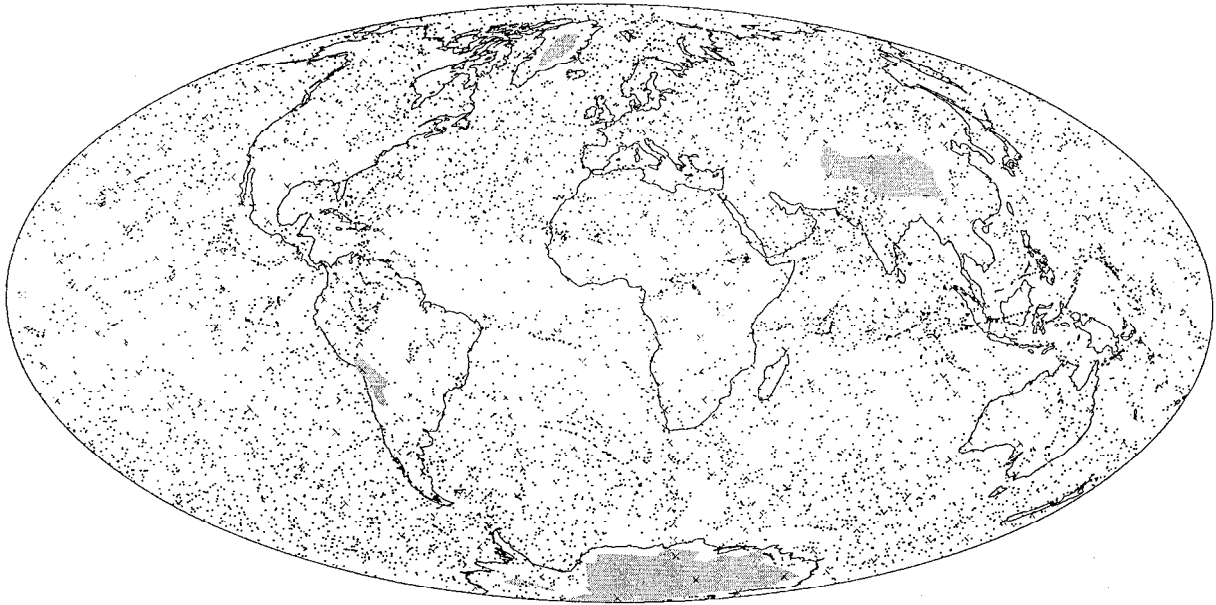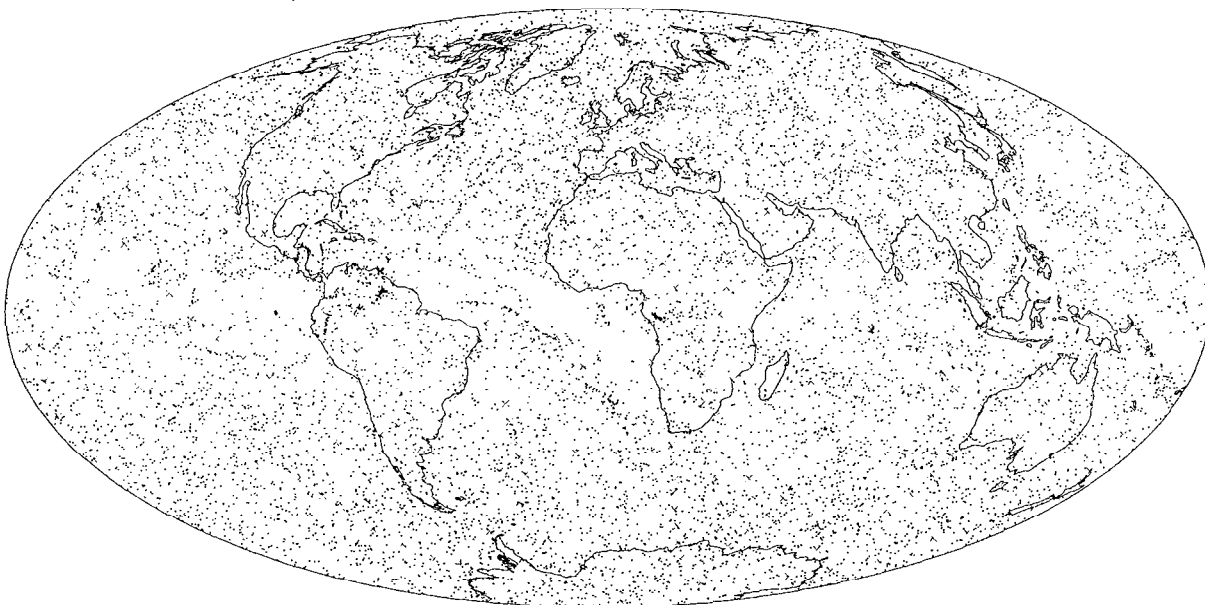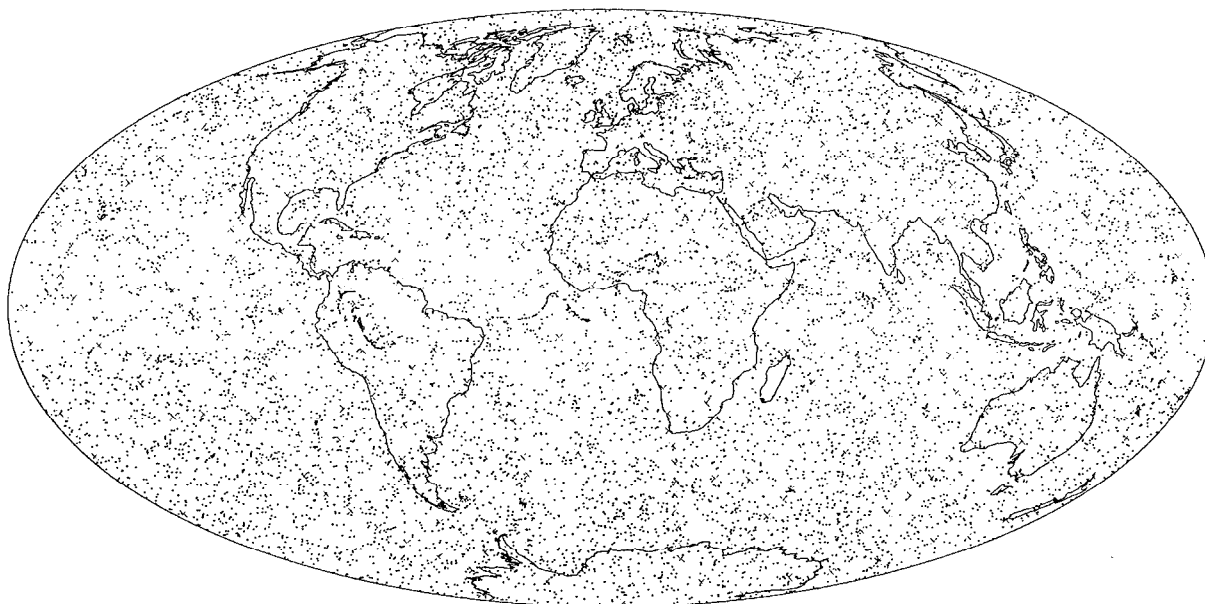
Figure 57. Location of balloons set for 775 mb after 35 days of daily releases from 298 launch sites indicated by ×. Terrain above 775 mb is shaded in gray. 10220 balloons released, 9597 still aloft, 623 hit terrain.

Figure 58. Location of balloons set for 700 mb after 35 days of daily releases from 298 launch sites indicated by ×. Terrain above 700 mb is shaded in gray. 10325 balloons released, 9992 still aloft, 333 hit terrain.
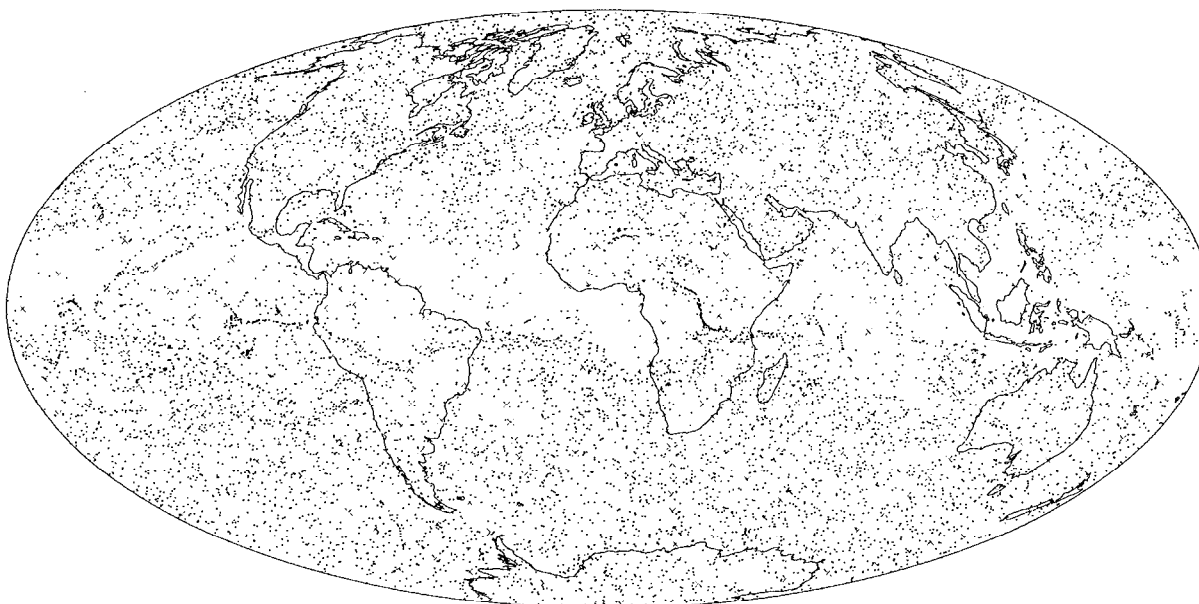
Figure 59. Location of balloons set for 600 mb after 35 days of daily releases from 298 launch sites indicated by ×. Terrain above 600 mb is shaded in gray. 10395 balloons released, 10189 still aloft, 206 hit terrain.

Figure 60. Location of balloons set for 500 mb after 35 days of daily releases from 298 launch sites indicated by ×. 10430 balloons released and aloft.
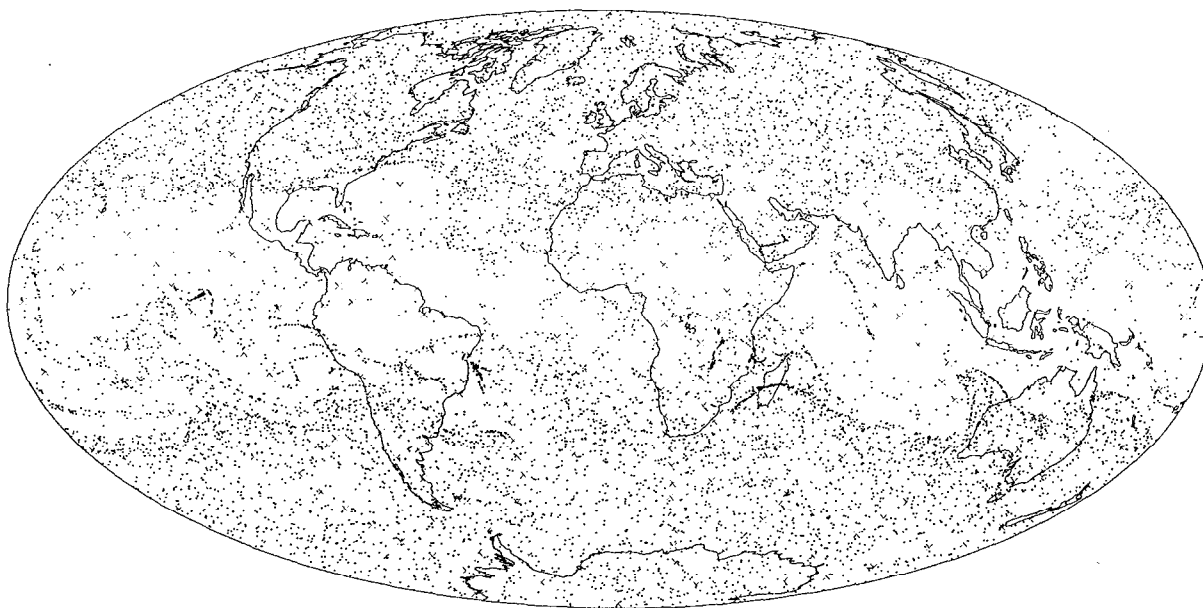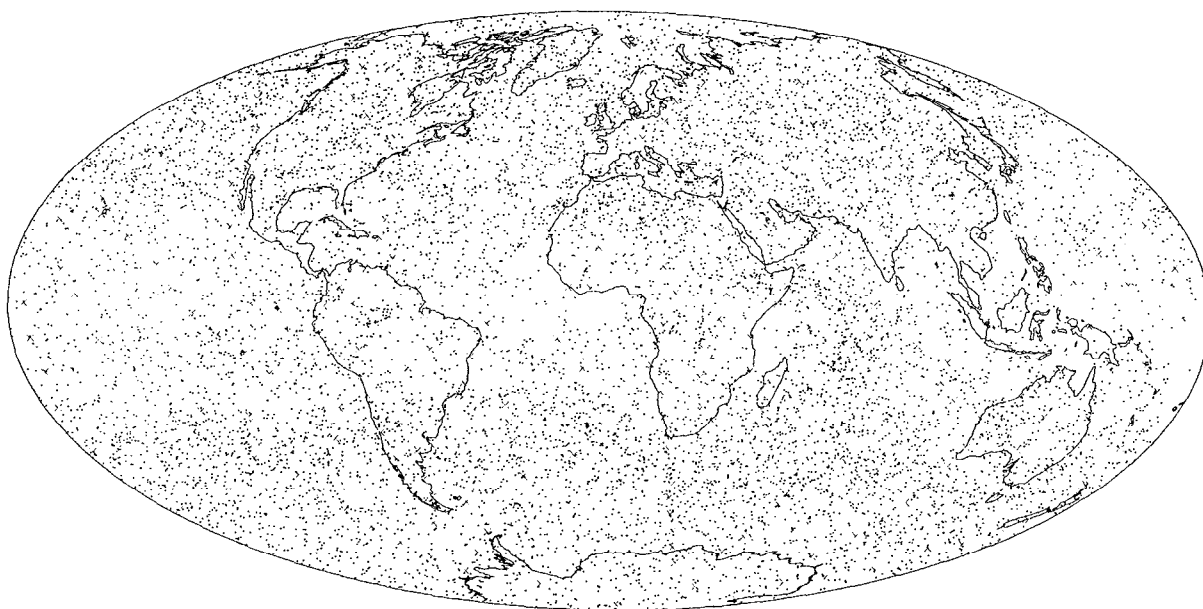
Figure 61. Location of balloons set for 400 mb after 35 days of daily releases from 298 launch sites indicated by ×. 10430 balloons released and aloft.

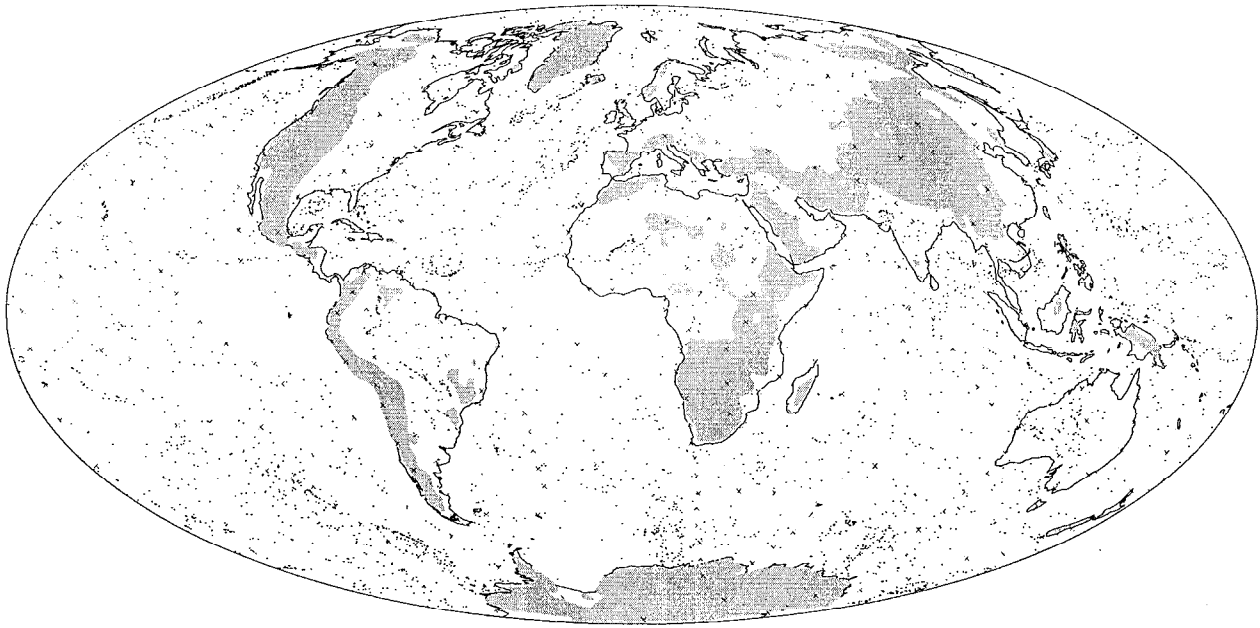**Figure 62**. Location of balloons set for 300 mb after 35 days of daily releases from 298 launch sites indicated by ×. 10430 balloons released and aloft.

Figure 63. Location of balloons set for 200 mb after 35 days of daily releases from 298 launch sites indicated by ×. 10430 balloons released and aloft.

Figure 64. Location of balloons set for 100 mb after 35 days of daily releases from 298 launch sites indicated by ×. 10430 balloons released and aloft.

2. NOGAPS/GRANTOUR

The NOGAPS/GRANTOUR simulation with daily balloon releases from 298 sites was run for 47 days. The higher spatial resolution of NOGAPS provides a better terrain distribution and a different number of active release sites for the lower floating-pressure levels. Table 5 gives the number of active release sites at each level and the fate of balloons after 35 and 47 days. Comparing Table 5 with Table 4 again shows that the higher resolution topography in the NOGAPS /GRANTOUR simulation results in a more rapid loss of balloons by terrain collisions.

The NOGAPS/GRANTOUR balloon locations after 35 days for the daily release scenario are plotted in Figures 65-74 and after 47 days in Figures 75-84. No significant differences exist between the CCM3 and NOGAPS simulations. The greater attrition of transponders by terrain in the NOGAPS simulation produces somewhat degraded coverage near the surface compared to CCM3 results. Nevertheless, the main problems remain. At low levels balloons are depleted from large portions of the tropics while they cluster into groups and bands in other areas. The tropical tropopause suffers a serious shortage of transponders, although not quite as severe as in the CCM3 case. In the middle levels of the atmosphere and above the tropopause, on the other hand, the transponders are distributed acceptably.

The best transponder distributions occur at the end of the NOGAPS/GRANTOUR simulation, i.e., after 47 days with daily releases from 298 sites. Better distributions after 47 days than after 35 days are mainly a result of the larger number of balloons aloft. However, the NOGAPS/GRANTOUR distribution at 925 mb after 47 days with only 5677 balloons aloft is considerably better than the CCM3/GRANTOUR distribution after 35 days with 6223 active balloons.

Table 5. Number of Balloons after 35 and 47 days for the NOGAPS/GRANTOUR Simulation

| Levels	Release Sites	Day 35			Day 47		
		Released	Crashed	Aloft	Released	Crashed	Aloft
100-500	298	10430	0	10430	14006	0	14006
600	298	10430	284	10146	14006	495	13511
700	295	10325	797	9528	13865	1210	12655
875	290	10150	1306	8844	13630	2070	11560
850	282	9870	2596	7274	13254	3863	9391
925	267	9345	4469	4876	12549	6872	5677

Figure 65. Location of balloons set for 925 mb after 35 days of daily releases from 298 launch sites indicated by ×. Terrain above 925 mb is shaded in gray. 9345 balloons released, 4876 still aloft, 4469 hit terrain.
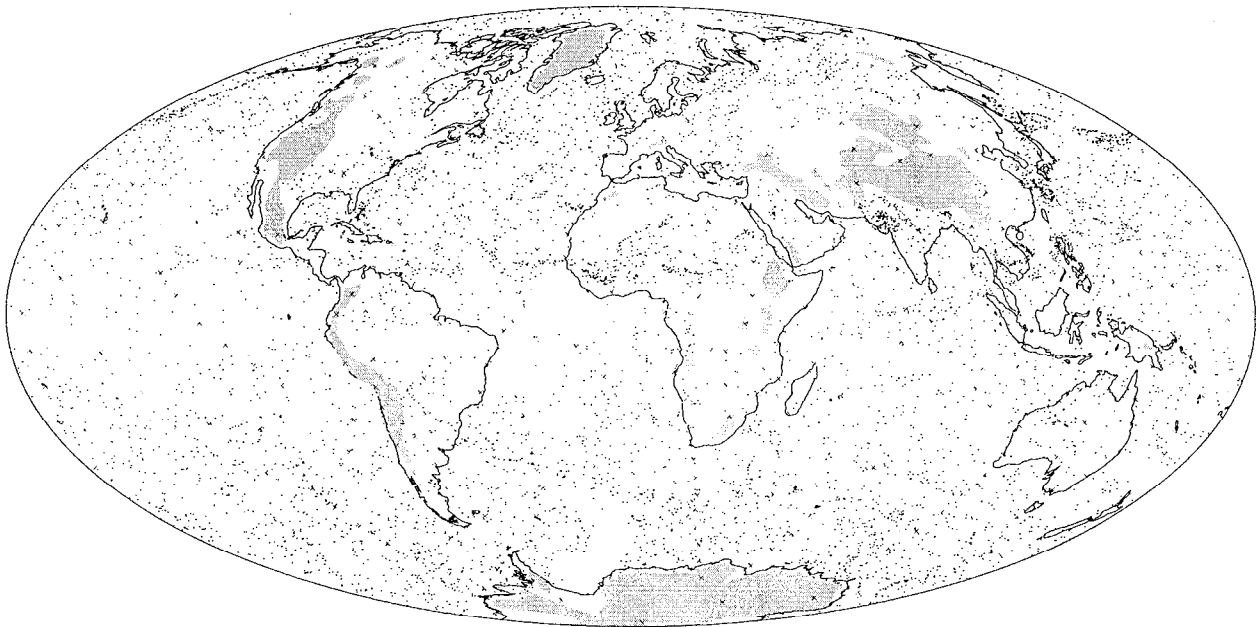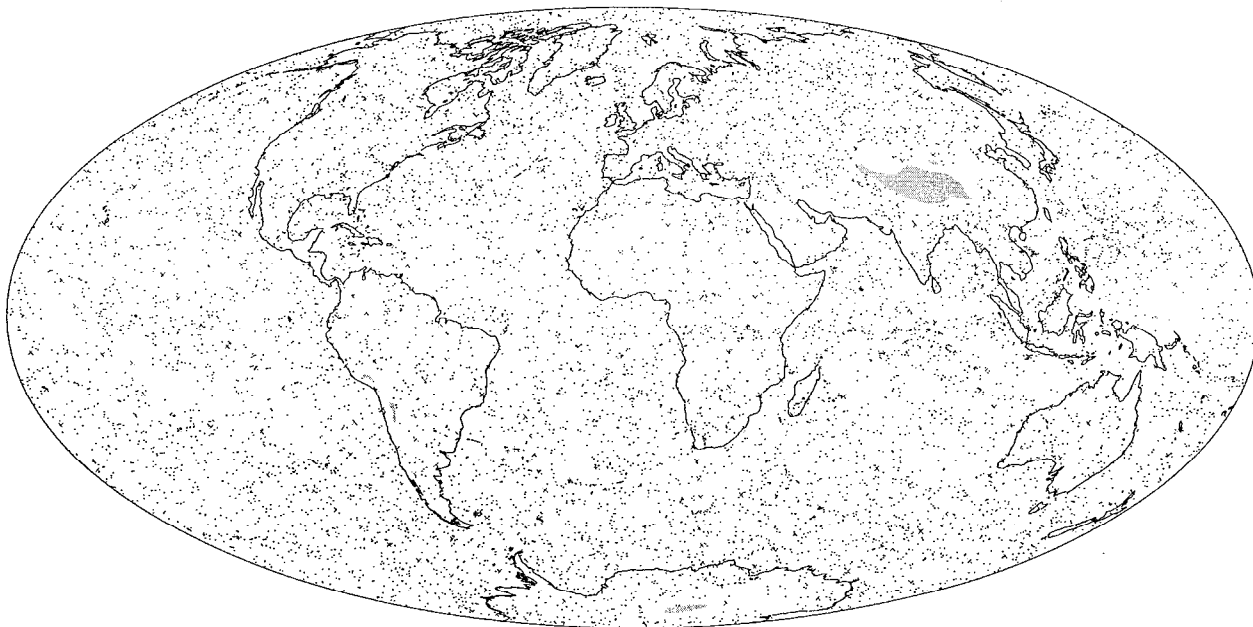

Figure 66. Location of balloons set for 850 mb after 35 days of daily releases from 298 launch sites indicated by ×. Terrain above 850 mb is shaded in gray. 9870 balloons released, 7274 still aloft, 2596 hit terrain.
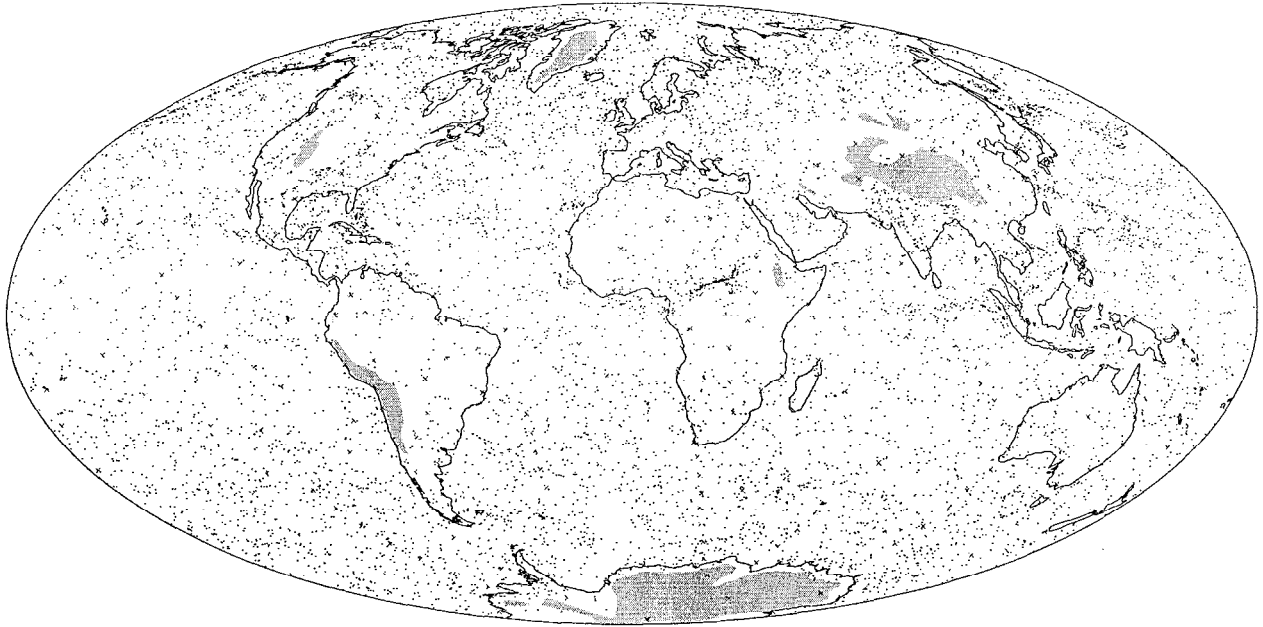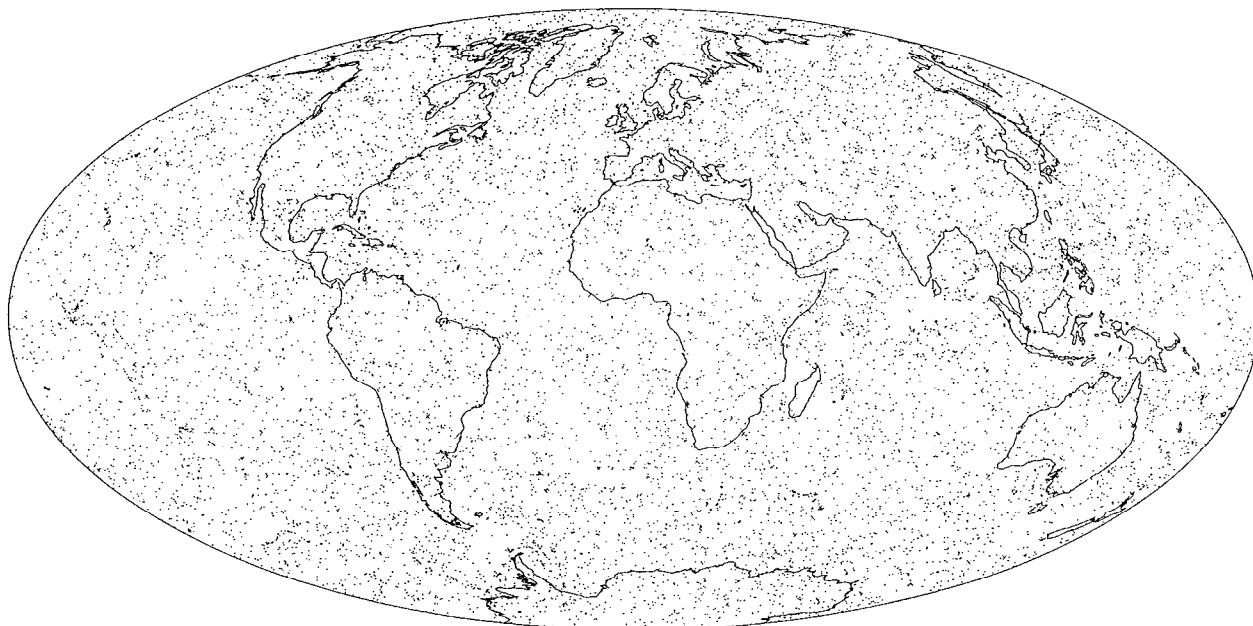
Figure 67. Location of balloons set for 775 mb after 35 days of daily releases from 298 launch sites indicated by ×. Terrain above 775 mb is shaded in gray. 10150 balloons released, 8844 still aloft, 1306 hit terrain.
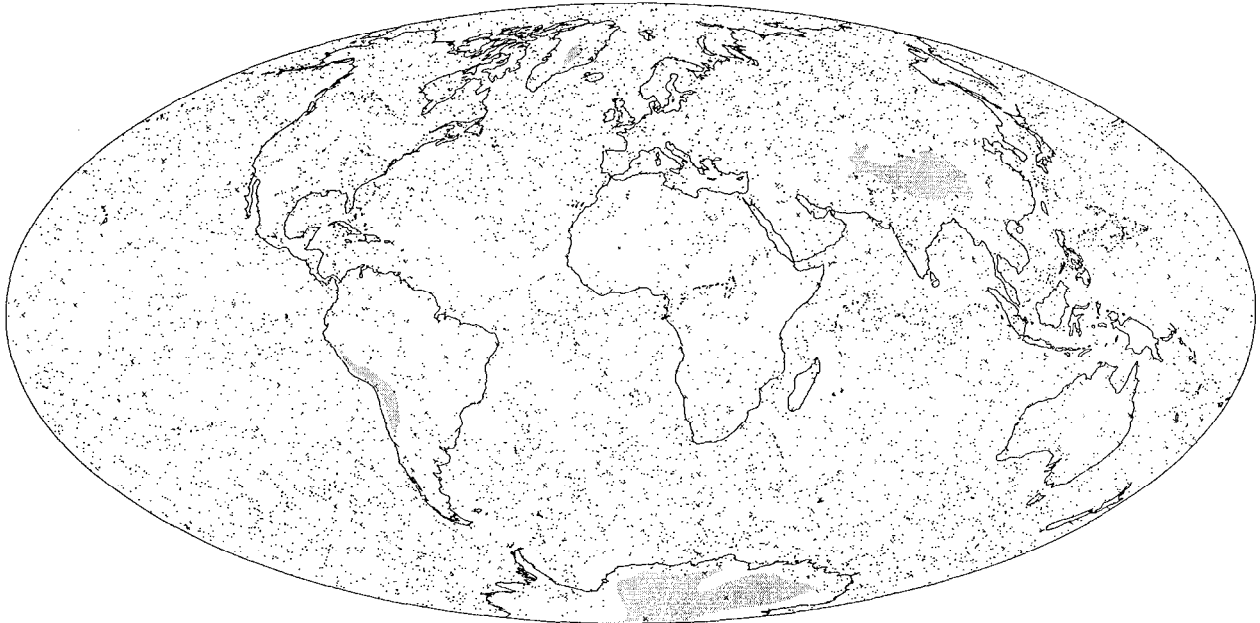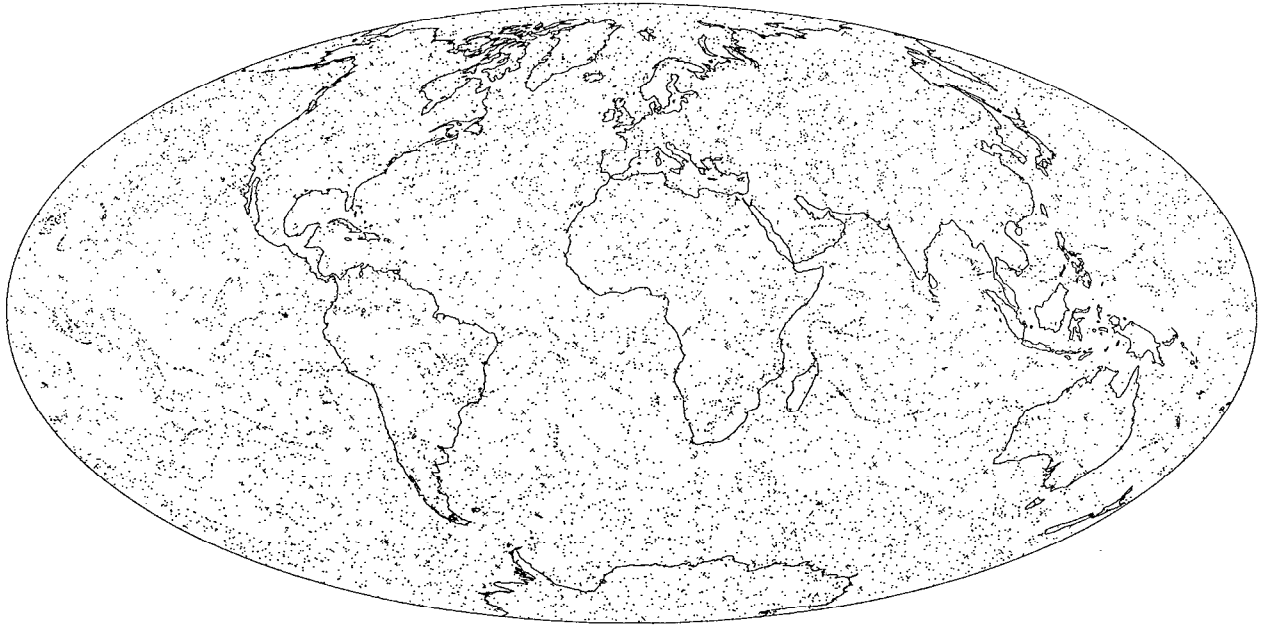

Figure 68. Location of balloons set for 700 mb after 35 days of daily releases from 298 launch sites indicated by ×. Terrain above 700 mb is shaded in gray. 10325 balloons released, 9528 still aloft, 797 hit terrain.
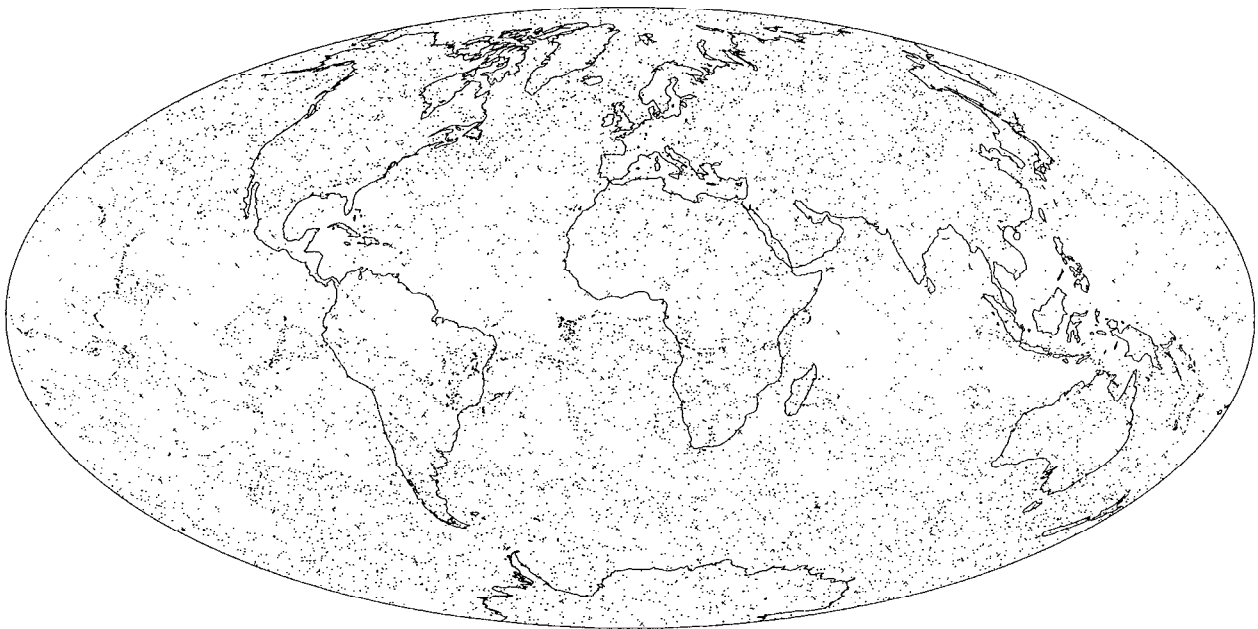
Figure 69. Location of balloons set for 600 mb after 35 days of daily releases from 298 launch sites indicated by ×. Terrain above 600 mb is shaded in gray. 10430 balloons released, 10146 still aloft, 284 hit terrain.
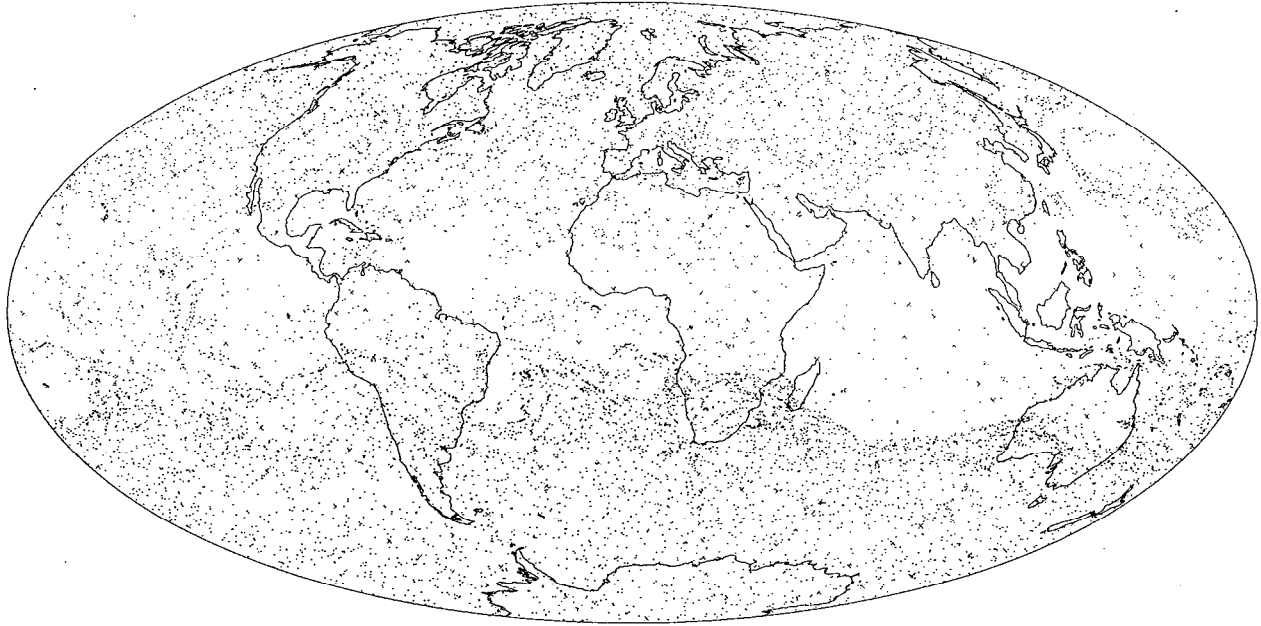

Figure 70. Location of balloons set for 500 mb after 35 days of daily releases from 298 launch sites indicated by ×. 10430 balloons released and still aloft.
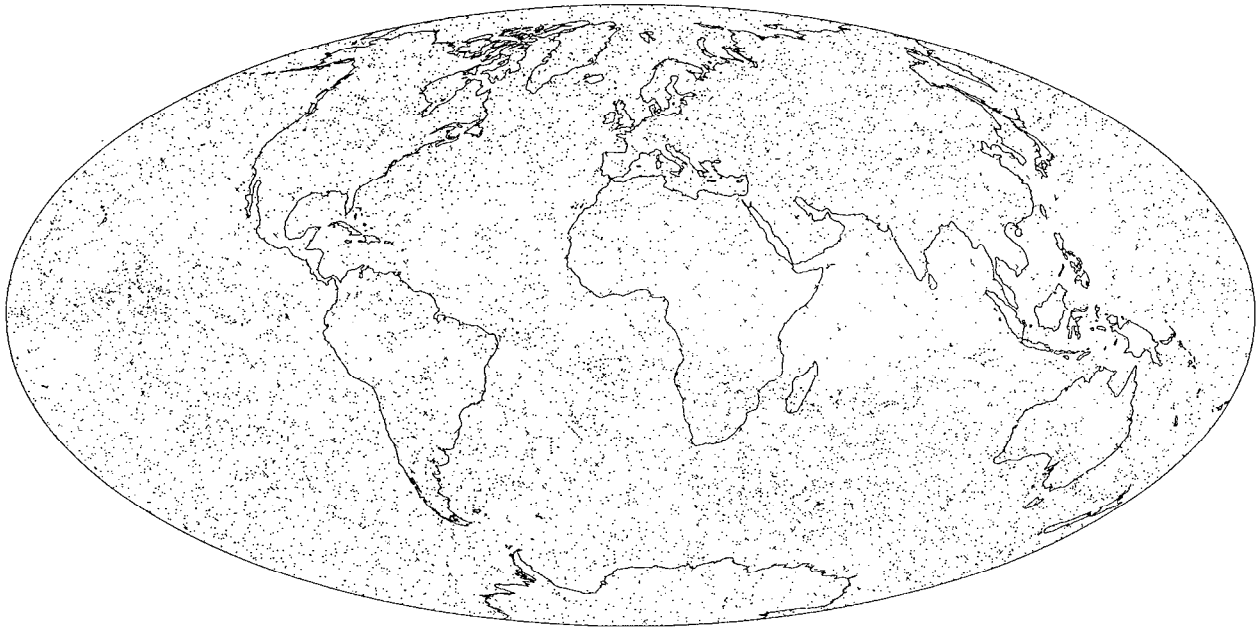
Figure 71. Location of balloons set for 400 mb after 35 days of daily releases from 298 launch sites indicated by ×. 10430 balloons released and still aloft.
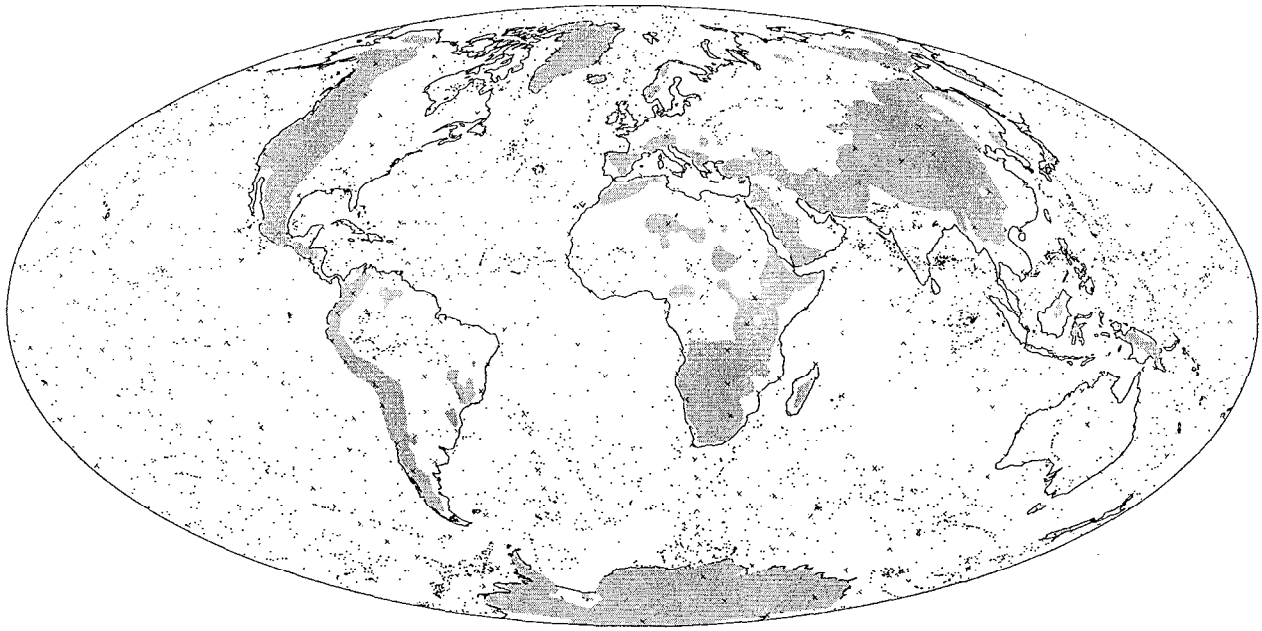

Figure 72. Location of balloons set for 300 mb after 35 days of daily releases from 298 launch sites indicated by ×. 10430 balloons released and still aloft.
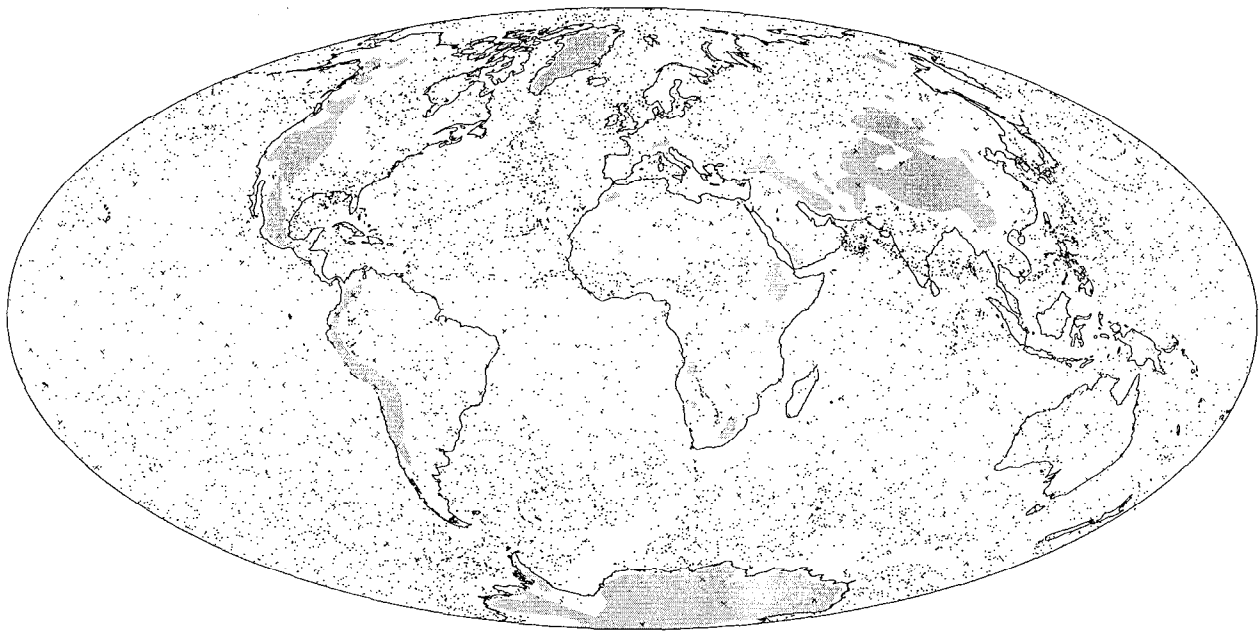
Figure 73. Location of balloons set for 200 mb after 35 days of daily releases from 298 launch sites indicated by ×. 10430 balloons released and still aloft.

Figure 74. Location of balloons set for 100 mb after 35 days of daily releases from 298 launch sites indicated by ×. 10430 balloons released and still aloft.
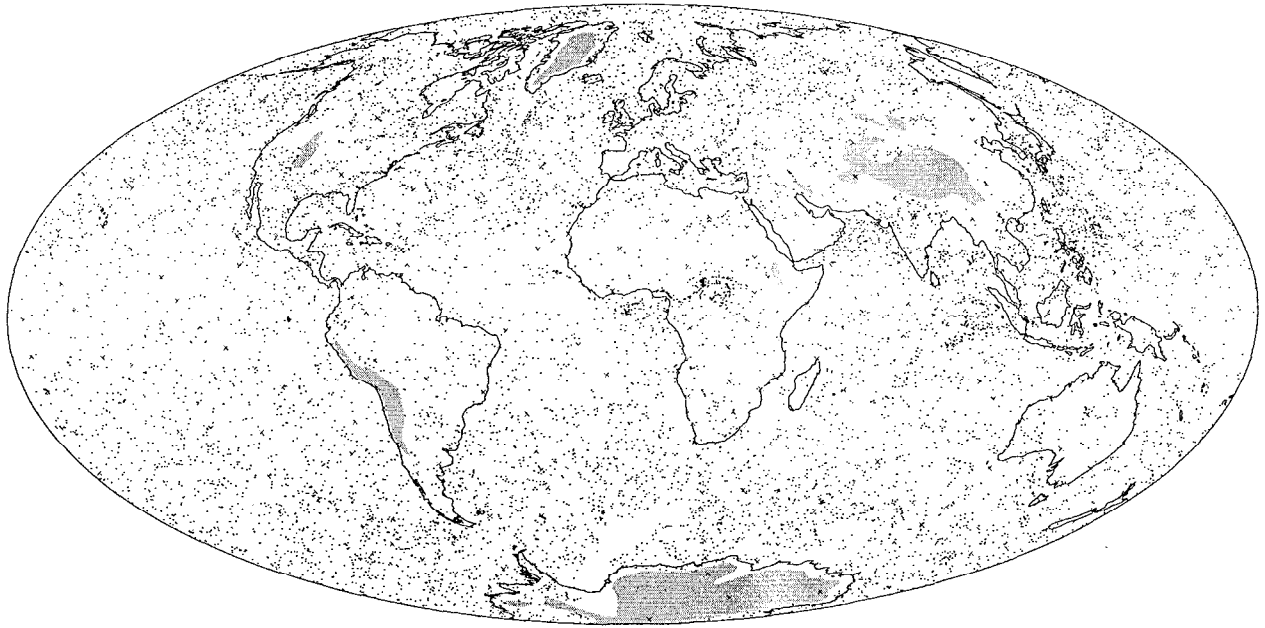
Figure 75. Location of balloons set for 925 mb after 47 days of daily releases from 298 launch sites indicated by ×. Terrain above 925 mb is shaded in gray. 12549 balloons released, 5677 still aloft, and 6872 hit terrain.
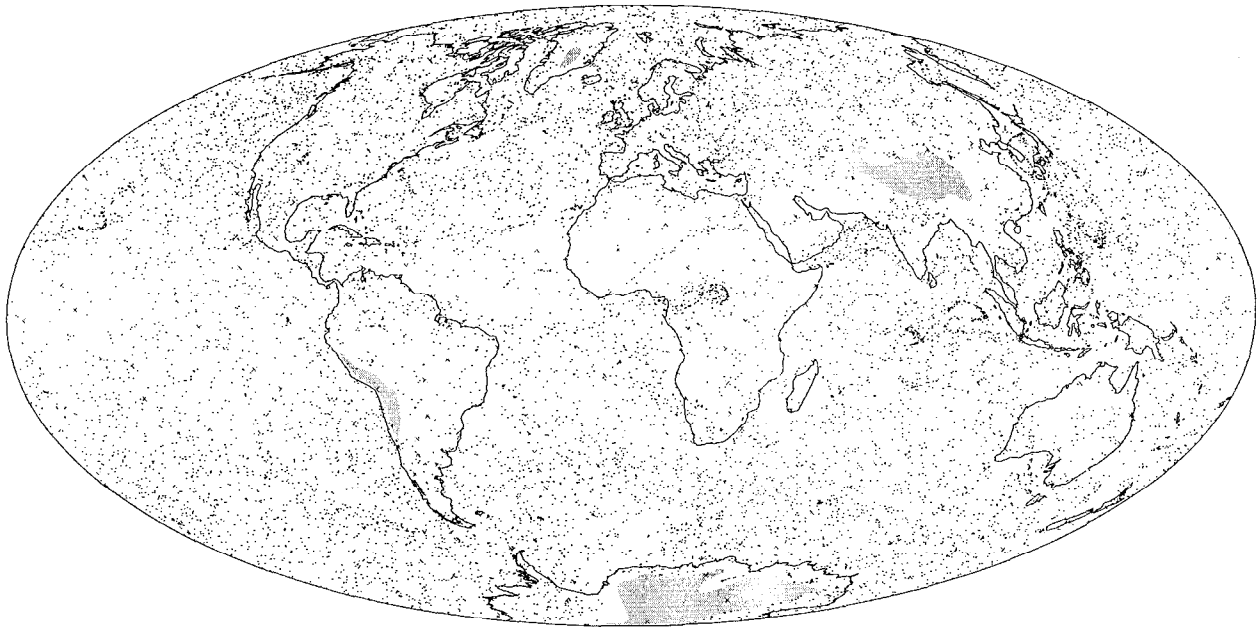

Figure 76. Location of balloons set for 850 mb after 47 days of daily releases from 298 launch sites indicated by ×. Terrain above 850 mb is shaded in gray. 13254 balloons released, 9391 still aloft, 3863 hit terrain.
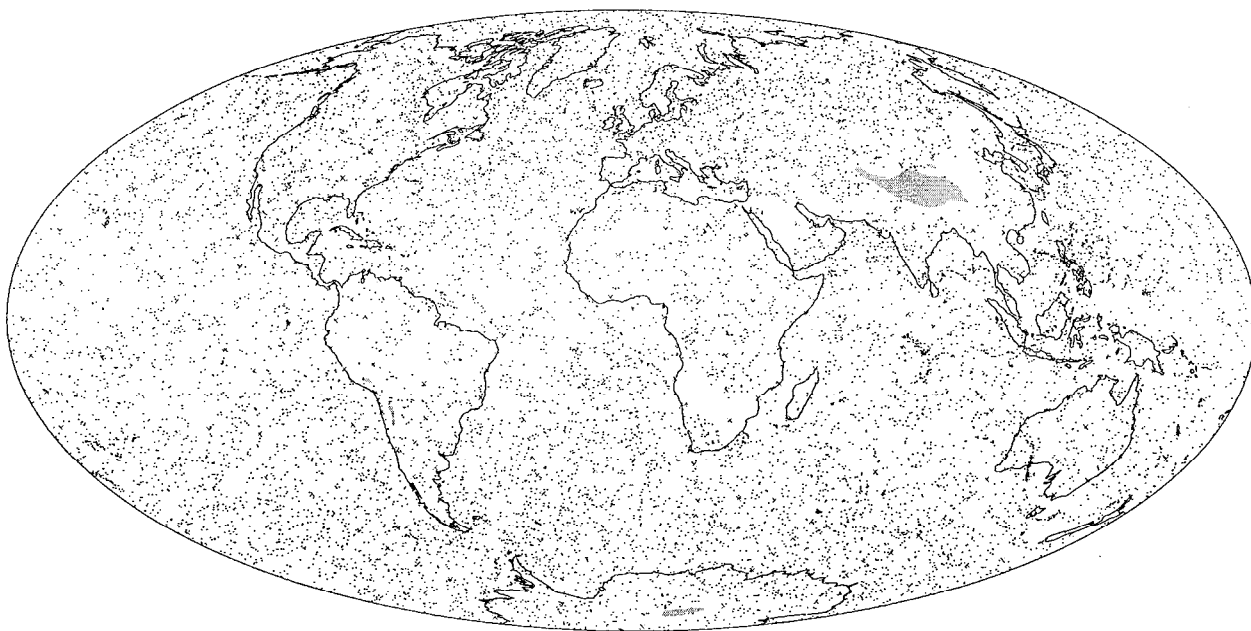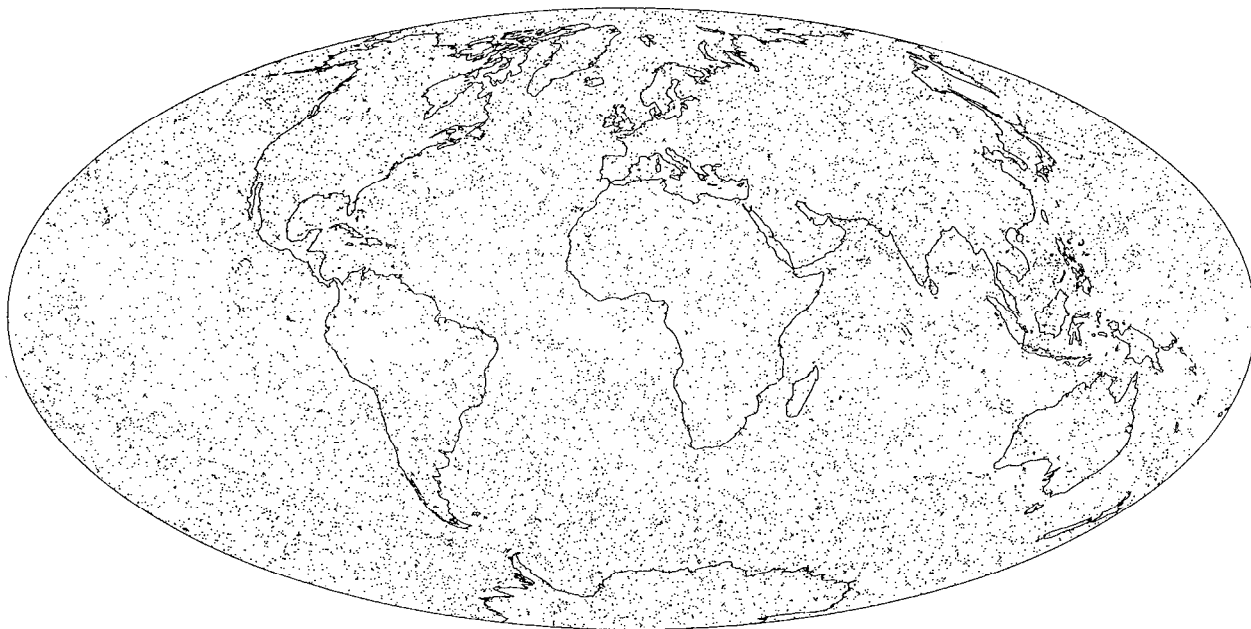
Figure 77. Location of balloons set for 775 mb after 47 days of daily releases from 298 launch sites indicated by ×. Terrain above 775 mb is shaded in gray. 13630 balloons released, 11560 still aloft, 2070 hit terrain.
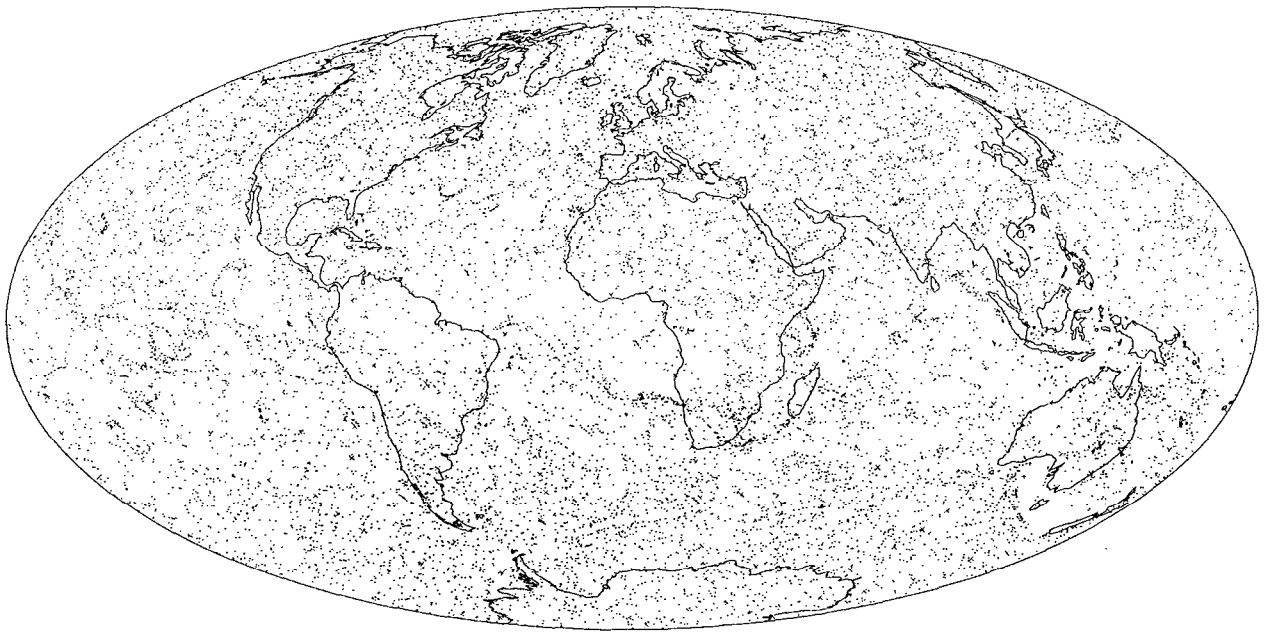

Figure 78. Location of balloons set for 700 mb after 47 days of daily releases from 298 launch sites indicated by ×. Terrain above 700 mb is shaded in gray. 13865 balloons released, 12655 still aloft, 1210 hit terrain.
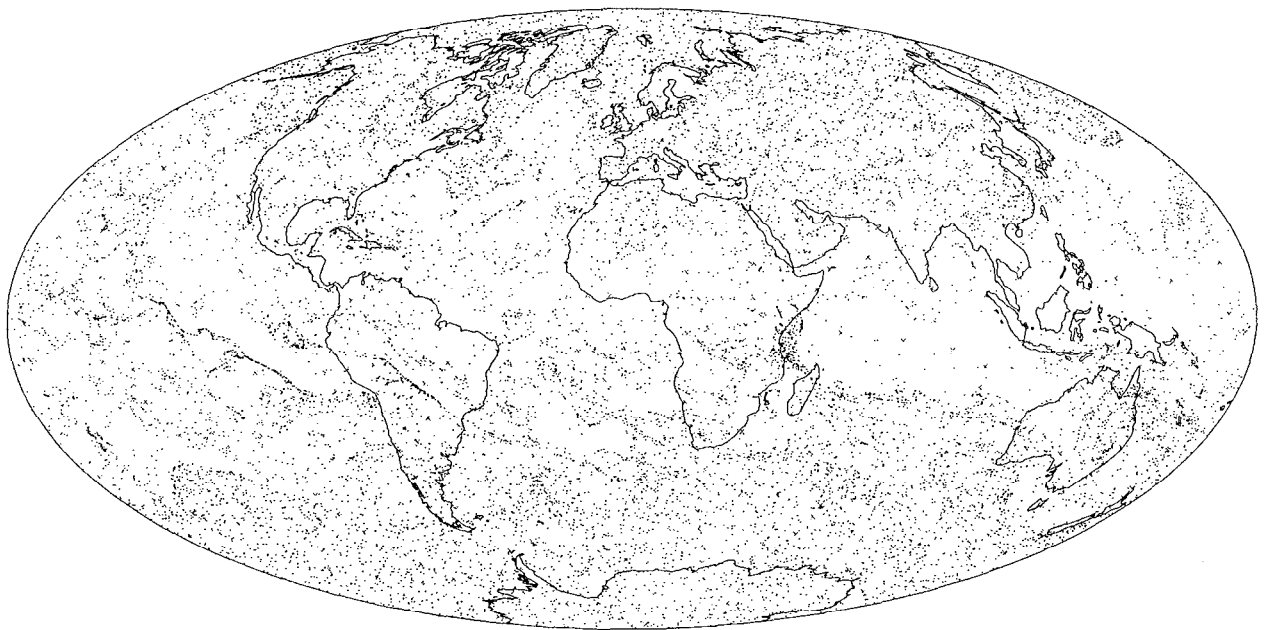
Figure 79. Location of balloons set for 600 mb after 47 days of daily releases from 298 launch sites indicated by ×. Terrain above 600 mb is shaded in gray. 14006 balloons released, 13511 still aloft, 495 hit terrain.

Figure 80. Location of balloons set for 500 mb after 47 days of daily releases from 298 launch sites indicated by ×. 14006 balloons released and still aloft.

Figure 81. Location of balloons set for 400 mb after 47 days of daily releases from 298 launch sites indicated by ×. 14006 balloons released and still aloft.

Figure 82. Location of balloons set for 300 mb after 47 days of daily releases from 298 launch sites indicated by ×. 14006 balloons released and still aloft.

Figure 83. Location of balloons set for 200 mb after 47 days of daily releases from 298 launch sites indicated by ×. 14006 balloons released and still aloft.
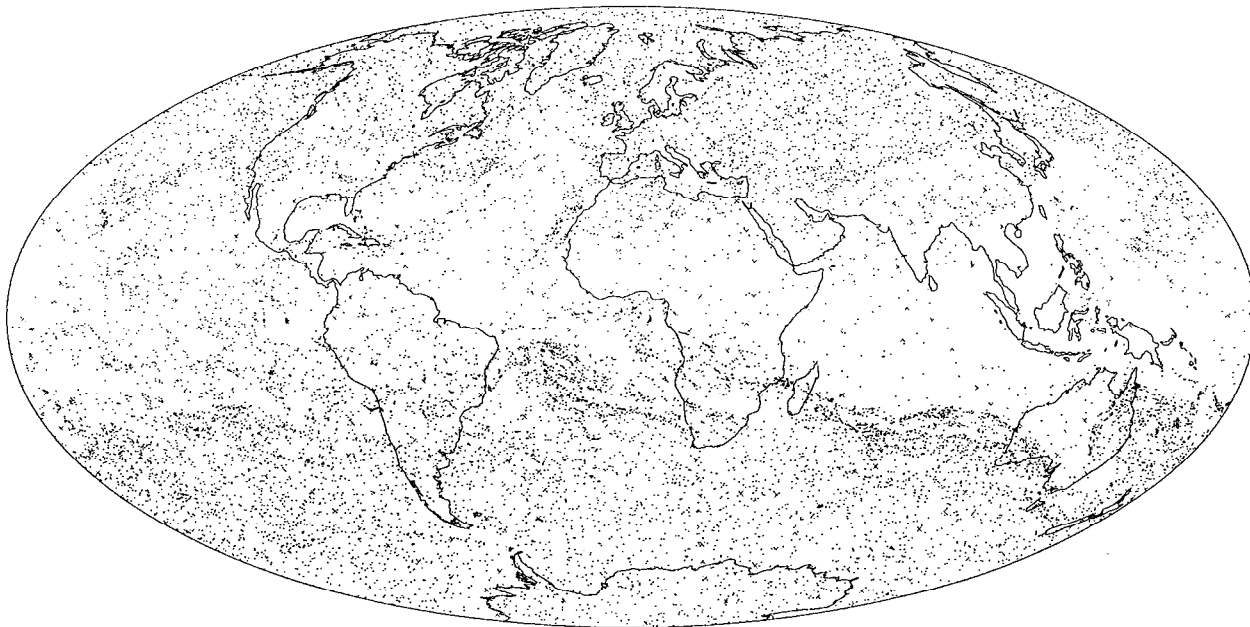

Figure 84. Location of balloons set for 100 mb after 47 days of daily releases from 298 launch sites indicated by ×. 14006 balloons released and still aloft.
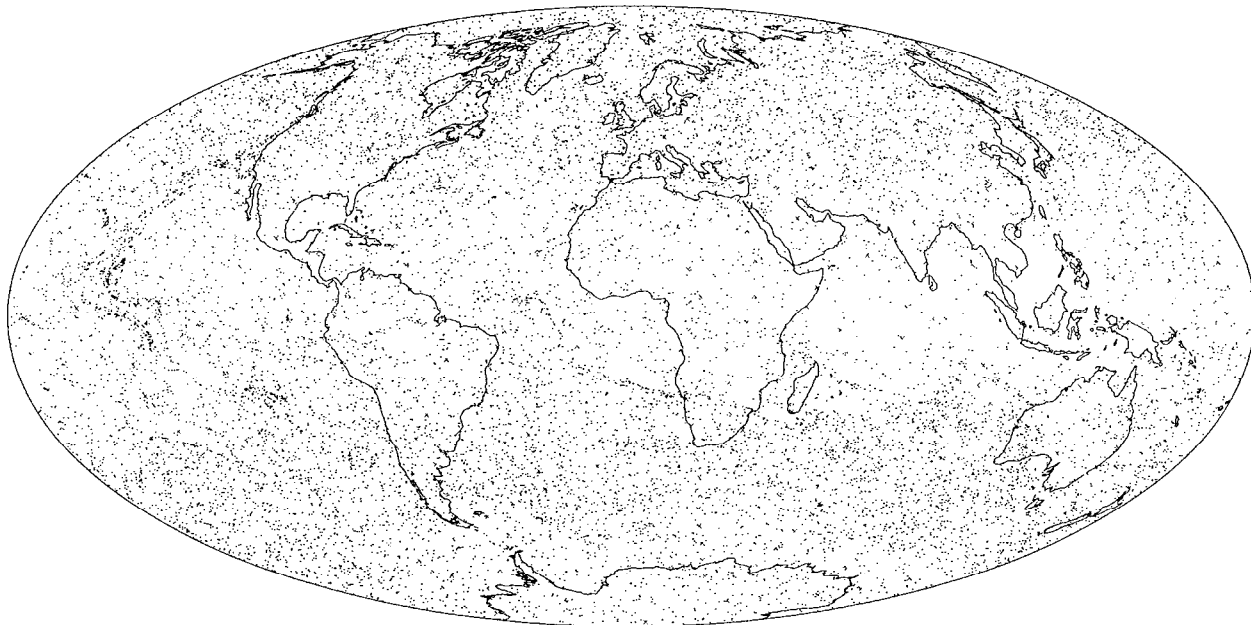
3. Vertical Sounding Coverage

For the daily release scenario, the feasibility of providing vertical profiles of wind and temperature to current NWP's can again be addressed by considering the number of vertical layers in columns with the NWP's horizontal resolution that contain at least one balloon. This information is plotted in Figures 85-86 for the CCM3/GRANTOUR simulation after 35 days and in Figures 87-90 for the NOGAPS/GRANTOUR simulations after 35 and 47 days.

Comparison of these plots for the daily release scenario to the corresponding Figures 49-54 for the initially uniform distribution revels a significant improvement. The fraction of the globe in warmer colors (red, orange, and yellow), where there is adequate coverage, is larger and the fraction in cooler colors (blue, purple, and black), where the data is too sparse to define a vertical sounding, is much smaller for the daily release scenario. Much of this improvement is due to a larger number of active transponders. However, comparison of Figures 85 with 87 and 86 with 88 shows that the NOGAPS/GRANTOUR simulation after 35 days gives better sounding coverage than the CCM3/GRANTOUR simulation even though CCM3/GRANTOUR has more active transponders.

For the NOGAPS/GRANTOUR simulation after 47 days and the horizontal sounding resolution grid with 64 latitude bands (Figure 90), many columns in the mid-latitudes have at least one transponder in each of the ten levels. Few columns have more than three levels with no transponders. Many of these are in regions of high mountains (Antarctica, Himalayas); the rest are in the tropics.

In summary, the daily release simulations produce global balloon distributions adequate to provide wind and temperature data for NWP's. The simulations with 298 release sites indicate that sufficient levels have at least one transponder to construct vertical temperature and wind profiles over the entire globe except the tropics. The shortage of transponders in the tropics is noted at all levels in both the uniform initial and daily release scenarios, but is worst near the tropopause and at the lowest levels. It needs to be addressed, probably by releasing more balloons in this region.

IV.   CONCLUSIONS

The feasibility of providing adequate wind and temperature data for initialization, data assimilation, and validation of NWP's has been demonstrated by transport simulations of an array of small balloon-bourne transponders. Horizontal distributions over the globe are very good in mid-latitudes and polar regions and in the mid-troposphere. Problem areas are the tropical tropopause, where balloons leave very rapidly and gather in bands at the edge of the Hadley circulation, and low tropical elevations, where balloon distributions become non-uniform due to well-known convergence/divergence patterns. In addition, loss of balloons via surface collisions leads to sparseness at low elevations. The low elevation problems are readily addressed by
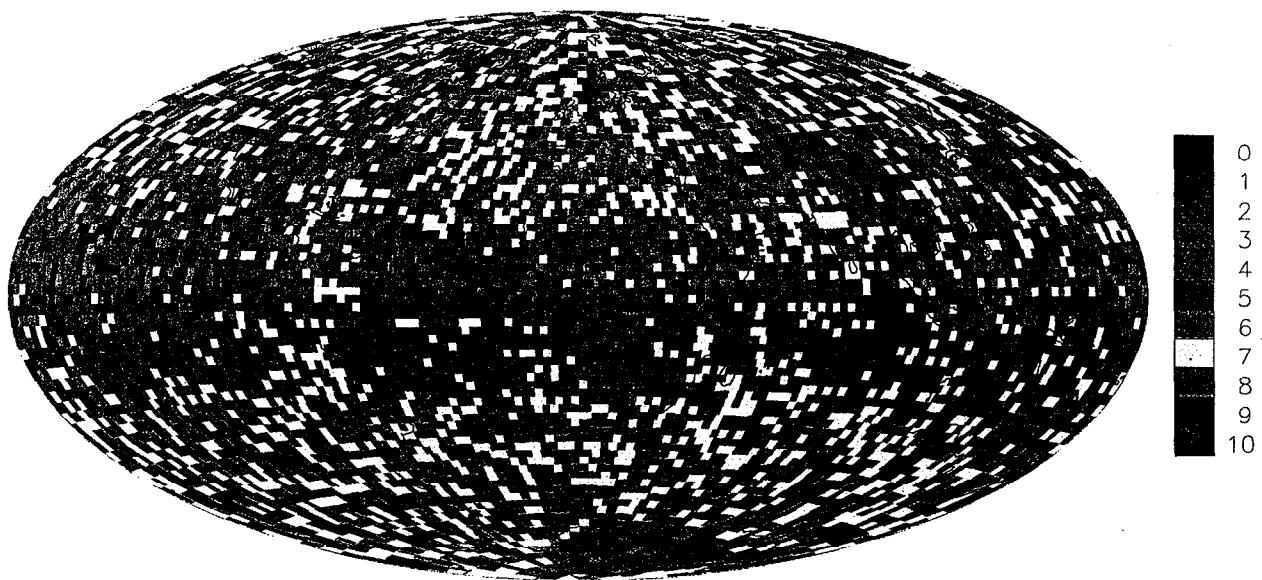
Figure 85. Number of vertical layers per horizontal column with at least 1 balloon for day 35 of the CCM3 wind data simulation for daily release from 298 sites. There are 80 equal area latitude bands and 8150 equal area columns of about 62,500 km² or 250 km on a side.
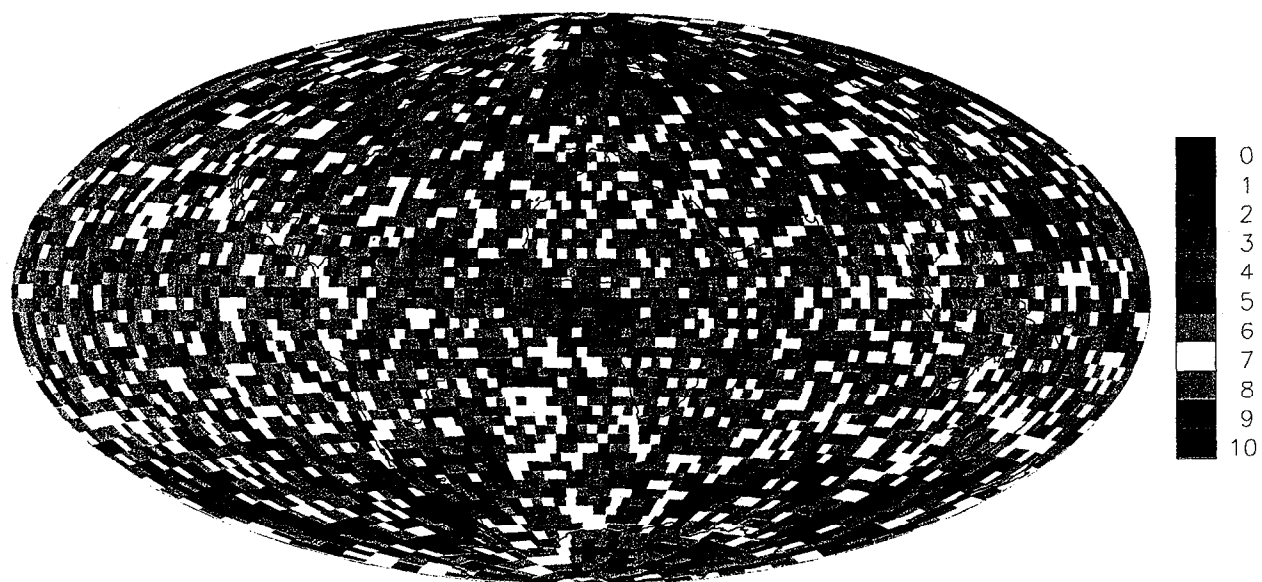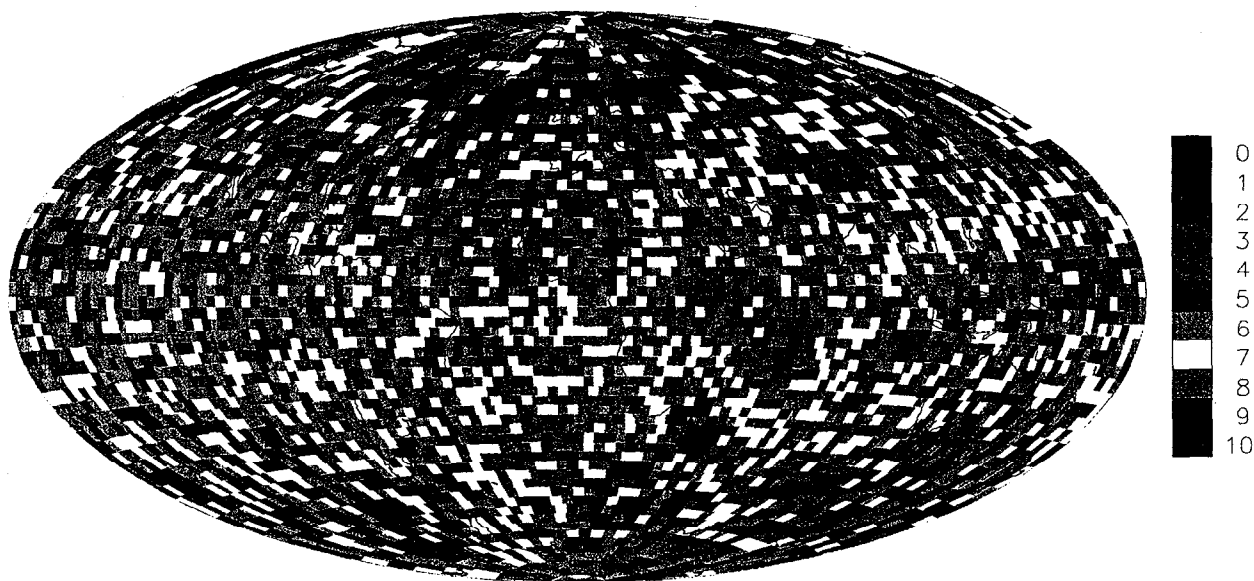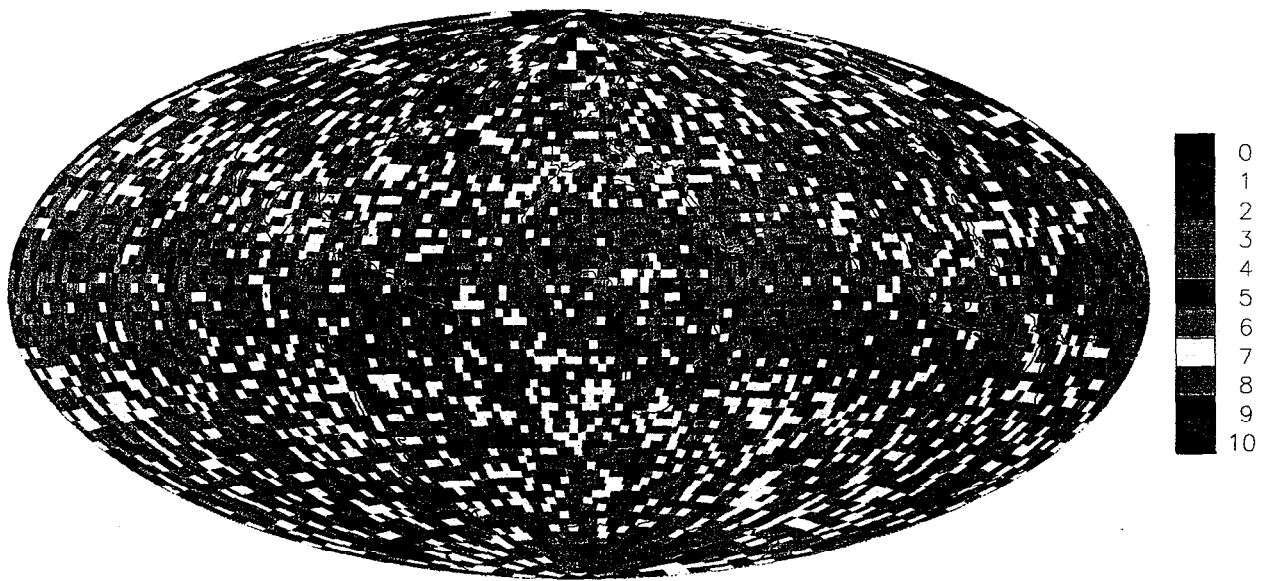

Figure 86. Number of vertical layers per horizontal column with at least 1 balloon for day 35 of the CCM3 wind data simulation for daily release from 298 sites. There are 64 equal area latitude bands and 5218 equal area columns of about 98,000 km² or 313 km on a side.
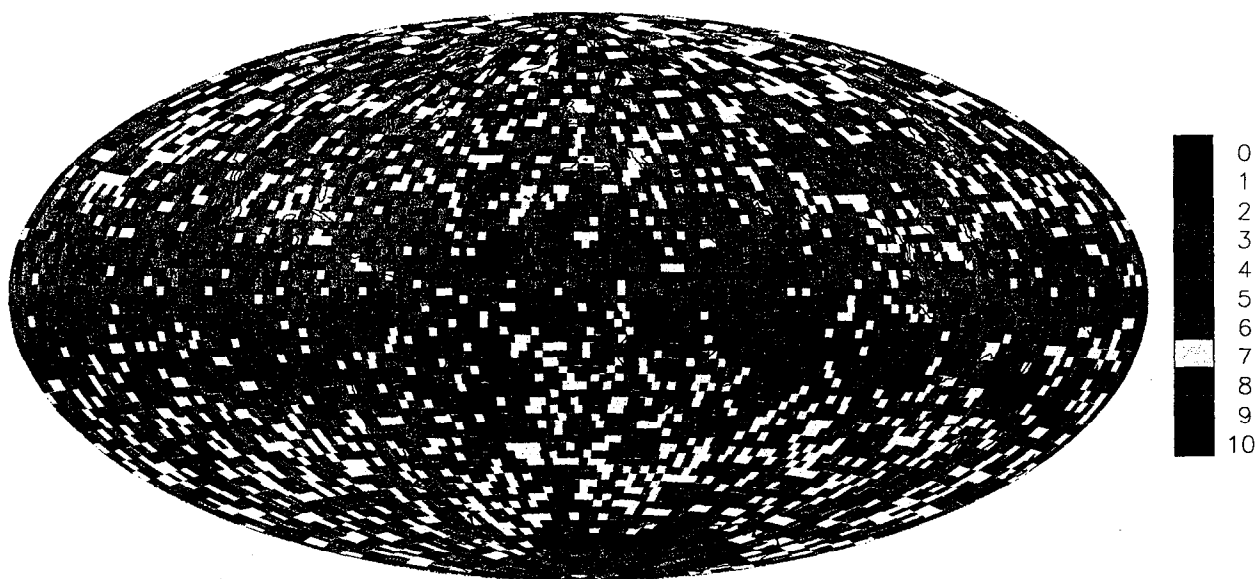
Figure 87. Number of vertical layers per horizontal column with at least 1 balloon for day 35 of the NOGAPS wind data simulation with daily releases from 298 sites. There are 80 equal area latitude bands and 8150 equal area columns of about 62,500 km² or 250 km on a side.

Figure 88. Number of vertical layers per horizontal column with at least 1 balloon for day 35 of the NOGAPS wind data simulation with daily releases from 298 sites. There are 64 equal area latitude bands and 5218 equal area columns of about 98,000 km² or 313 km on a side.

Figure 89. Number of vertical layers per horizontal column with at least 1 balloon for day 47 of the NOGAPS wind data simulation with daily releases from 298 sites. There are 80 equal area latitude bands and 8150 equal area columns of about 62,500 km^2 or 250 km on a side.
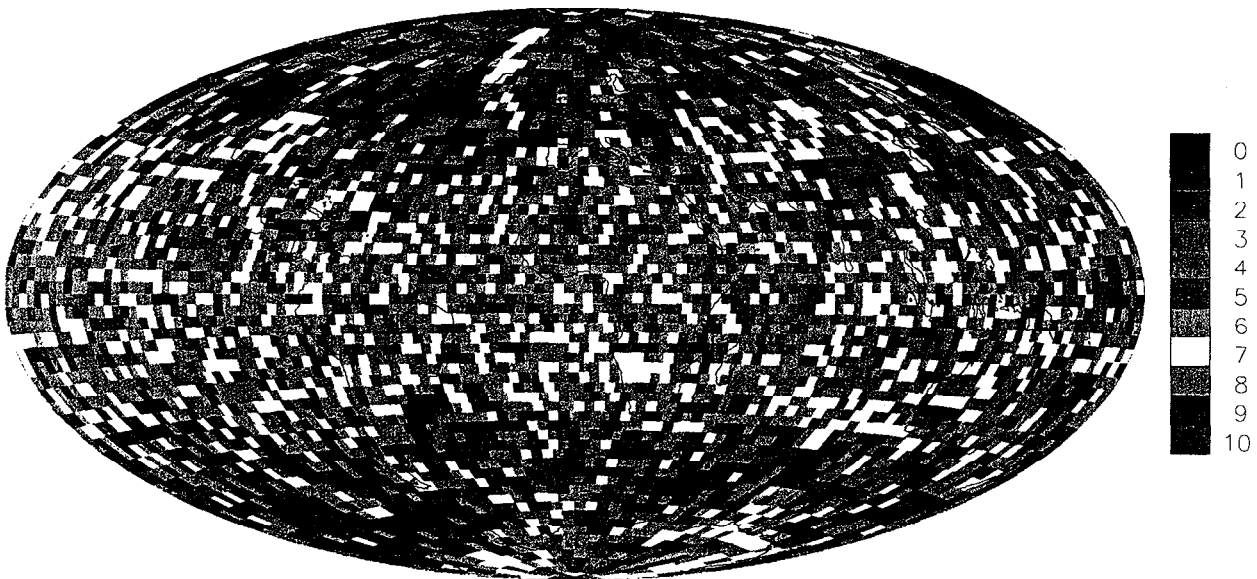

Figure 90. Number of vertical layers per horizontal column with at least 1 balloon for day 47 of the NOGAPS wind data simulation with daily releases from 298 sites. There are 64 equal area latitude bands and 5218 equal area columns of about 98,000 km^2 or 313 km on a side.

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launching additional balloons, but the rapid divergence of balloons from the tropical tropopause is not easily neutralized.

While the initial results reported herein are promising, several additional effects need to be studied further. These include simulation of a full annual cycle to remove seasonal bias, optimization of the sequential launch scenario, more realistic representation of balloon vertical motion including changes in balloon density by heating/cooling and water loading, higher density of release sites, addition of vertical floating-pressure or neutral buoyancy levels, incorporation of diffusion in the horizontal velocity, and inclusion of more balloon loss processes.

The only balloon loss mechanism included in this study is terrain collision, but balloons also fail for other reasons including defects in manufacture, skin deterioration, and crashes with airplanes and birds. Also, a balloon's buoyancy changes with time as air and helium (or other lighter-than-air gas) diffuse through its skin; therefore, the assumption that a balloon maintains its floating-level pressure for a long time is unrealistic. In addition, a balloon's surface absorbs and emits thermal radiation, so its temperature will change. At night, water vapor will very likely condense on balloons, greatly reducing their lift and perhaps causing them to hit the ground. Finally, as balloons move through clouds, they accrete liquid water and/or ice, and that reduces or destroys their buoyancy. Such balloons could easily be dragged to the ground, especially where water loading and downdrafts are correlated.

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